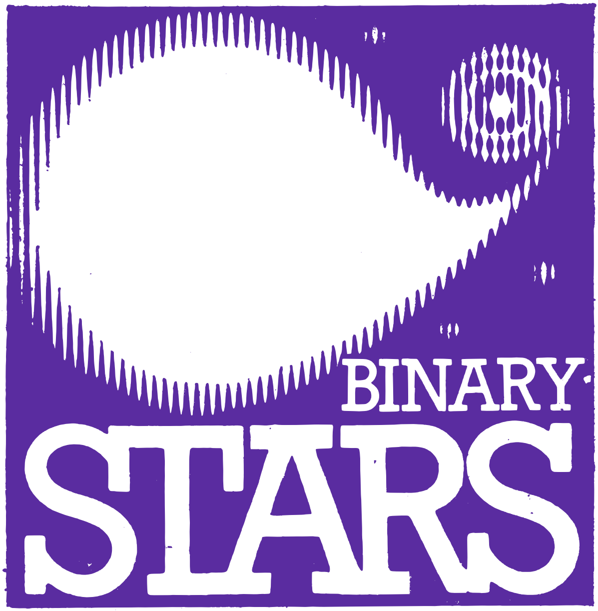
SCIENCE FOR EVERYONE

V. M. LIPUNOV

IN THE WORLD OF



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V.M. Lipunov

In the World of Binary Stars

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Contents

Preface

Many of the stars in our Galaxy are binary. I daren't say most for neither the exact number nor the relative fraction of binaries are yet known. That they account for at least ten percent of all the stars is so far as much as we know. Some estimates, though, come close to 90%. This, however, is not the only or even the major reason why binary stars draw researchers' attention. In fact, there are two reasons for their interest.

The first one is purely practical. A single star is very difficult to study. The scientists' task is much easier when it has a companion. In a way, the binary arrangement is more "approachable" and lets astronomers attempt to understand it.

The second reason is that a binary star has a fascinating life. It is much more fun to explore a binary. To see a star coupled with another is like finding another dimension. The life of a couple is more varied than that of a loner just like a plane is richer than a line or a space is richer than a plane.

Although mankind has been exploring binary stars for several centuries, it has only been in the last decades that we have come to understand the laws governing their existence. An especially great amount has been done in the last 10-15 years thanks to the new science of X-ray astronomy. In binary star science, two rivals, theory and fact, take part in a never-ending race in which they push each other forward to unpredictable and stupendous discoveries.

By today, our understanding of star life has changed dramatically. There has also been a change of attitude, and we now live in a permissive world. Could you imagine a serious astronomer of the 1950s describing one star as "swallowing" its neighbour? At present, this topic is a major issue investigated by observers and theorists. Could you imagine that in our Galaxy there are objects that owe their lives entirely to the existence of gravitational waves? Nature utilizes as a matter of routine what physicists have been trying to record for decades.

The diversity of the physical processes occurring in binary stars is greatly interesting and they are often comprehensible only to a researcher who has knowledge in nearly every branch of today's physics. An attempt to go into all the new and interesting developments in binary star science would be both unnecessary and futile. I shall not try to do the impossible.

In this book, I sought to present the fundamental ideas which have paved the way to major research developments. When I was short of words, I took pen and ink and drew something.

The exploration of binary stars continues and new horizons are coming within reach. I am sure that in years to come my readers will witness fascinating developments or even make important discoveries in this field themselves.

I dedicate this book to the memory of Vera Lipunova, my mother. She was also my first teacher as she was for many others.

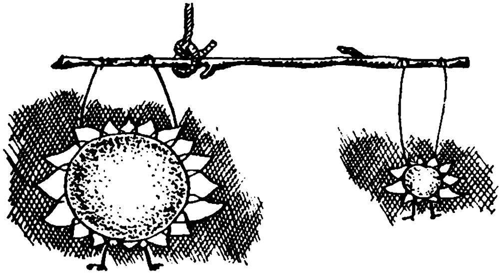
I also want to express my profound gratitude to N. A. Lipunova for her help in discussing the text and preparing the manuscript for the press. I am also grateful to T. A. Birulya for her help with the illustrations.

Vladimir Lipunov

Chapter 1

What Is a Binary Star?

The first answer that comes to mind is that a binary system is a pair of stars that are held together by their gravity. This statement, however, doesn't define binaries because any two stars, like any two masses, are attracted to each other by gravity. That means that every star comes within this definition and thus it is utterly useless. To understand what a true binary is, let us first simplify the situation.



Imagine a universe with nothing but two stars. It may be represented by a blank sheet of paper with two points, *1* and *2*, each showing a star with masses M_1 and M_2 respectively (Fig. 1). Let us find the centre of mass of the two stars (we label it O). To bring it closer to reality, we must for a moment come back to the normal universe, or to Earth. We connect the two masses, M_1 and M_2, with a weightless rod

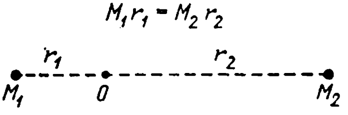


Fig. 1. The distance between the centre of mass and the stars is inversely proportional to their masses. O is the centre of mass of the binary

and suspend it with a string so that the rod is in a horizontal position. The point on the rod to which the string is tied is the centre of mass O of the binary star system.

So we only have two stars and we have their centre of mass. Now we can make a good definition. The two stars comprise a binary system if they travel within a certain *limited* space. Purely kinematic, this definition is just as good as one based on energy, namely, a star system is binary if its total energy is negative. According to Newton's laws of motion and the law of universal gravitation, the requirements of limited space and negative energy are interchangeable. To prove this, you don't have to know exactly how the bodies attract each other. What is important is to realize that, as the distance between the bodies increases, the gravitational force decreases rather rapidly. Let us prove it by contradiction. We assume that the stars' total energy, which is composed of kinetic and potential energies, is negative and that the stars are infinitely far apart. Characteristically, their total energy remains constant while the energy of the gravitational attraction, i.e. the potential energy, falls to zero. Now the stars' total energy is entirely made up of their kinetic energy, which is at least not negative. Here we have a contradiction. Hence bodies which have a negative total energy cannot move infinitely far apart.

This general definition is not, however, particularly lucid. First, we are surrounded by a multitude of stars, and so perhaps the definition is only theoretical. Second, we should have a better understanding of how stars move in a binary system.

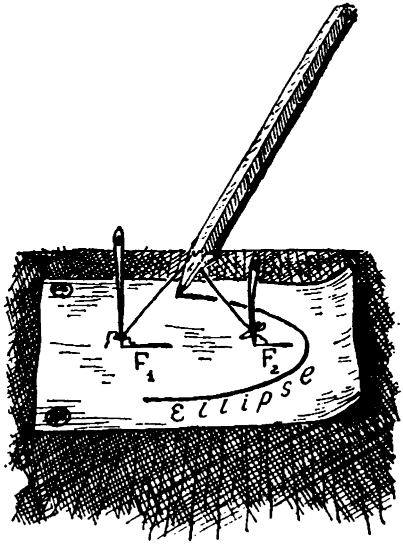
The first objection is not valid because the Universe, and even our Galaxy, has enough space for two stars to find a spot to enjoy their privacy. As for the laws which govern the motions of two companions, they are discussed below.

Kepler's Laws

After graduating from the University of Tübingen in 1593 the famous German astronomer Johannes Kepler was made professor of mathematics and moral philosophy at a high school. This means he made his first steps in science 17 years before the telescope was invented. He was destined to become a great theorist and an outstanding experimentor. Six years before Galileo pointed his telescope at the sky, Kepler wrote a book about the application of optics to astronomy. Today's school telescopes, in which both the objective and the eyepiece magnify, were invented by Kepler in 1611.

Yet his most astonishing discoveries came from the tip of his pen. Kepler was not what we now call a theorist but rather a master of interpretation. It is commonly believed that interpretation implies neither observation nor theorizing and an interpreter only arranges facts and traces regularities. This, however, is not always true. Kepler was a devout believer in the fundamental harmony of the world. Though at times this faith took him too far, he placed primary reliance on observation.

In 1601, Kepler "inherited" a priceless treasure, the great astronomer Tycho Brahe's archives. Kepler spent nine years analyzing the observation of Mars. Scholars at the time did not write scientific articles for there were no periodicals where they could be published; instead they wrote books. Kepler published his analysis of the motion of Mars based on Tycho's observations in his books *Astronomia Nova* and *Commentaries* *on the Motions of Mars.* In these books, Kepler stated for the first time that the orbit of Mars is an ellipse with the Sun at one focus. Recall that an ellipse is a closed plane curve consisting of all the points for which the sum of the distances



How to draw an ellipse

between a point on the curve and two fixed points (the foci) is the same. It is easy to draw an ellipse. Take two needles and pin them to a sheet of paper. The pinholes will be the foci of the ellipse. Take a piece of string and tie its ends to the needles. Then pull the string tight with a pencil and move the pencil slowly. Since the string remains constant in length the shape being drawn will be an ellipse.

Kepler also noticed that Mars moves slower when it is farther from the Sun and faster when it is close. Kepler never stopped

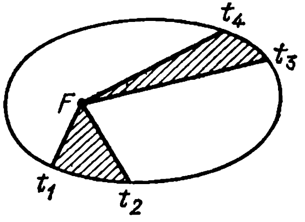


Fig. 2. In equal time intervals ($t_2 - t_1 = t_4 - t_3$), a planet's radius-vector sweeps equal areas (Kepler's law)

searching for beauty and harmony. It turned out that the areas swept by the planet's radius-vector in equal time intervals are equal (Fig. 2).

Ten years later Kepler wrote another book, *Harmony of the World*, in which he demonstrated that the other planets orbiting the Sun behaved in the same manner as Mars. In other words, each planet's orbit is an ellipse with the Sun at one focus (Kepler's first law) and the radius-vector of the planet sweeps equal areas in equal time intervals (Kepler's second law). The reader may wonder what all this has to do with beauty and harmony and what is the big difference between an oval and an ellipse. Before I answer try to draw an ellipse. Though it is a matter of taste, you will probably admit that it is much more beautiful because it is a shadow of a circle, which is the most symmetric plane figure. The projection of a circle is an ellipse, not an oval. Probably that's what makes it so beautiful.

In Kepler's laws, there is another kind of harmony which has a profound physical meaning. It is surprising how planets, which are so far apart and which seem to live on their own, know that they should move along elliptical orbits. When you draw an ellipse on a sheet of paper everything is clear for there is a string holding the pencil. By changing the length of the string you can draw many figures, but they will all be ellipses. It follows that there must be some kind of string in the Universe too. Kepler saw much beauty and harmony in these "strings", which set the worlds in motion and which cannot be seen by a human eye. Another astonishing regularity in planets' motions he discovered proves he was right. Kepler's third law is that the squares of the periods of revolution of any two planets are proportional to the cubes of the semimajor axes of their orbits.

The semimajor axis is half the distance between the two most distant points of an ellipse.

What are these invisible strings? It became more clear at the beginning of the 20th century with Albert Einstein's general relativity. As far back as in the 17th century, however, Isaac Newton also yielded a much better vision of the world by replacing Kepler's three laws with the *law of universal gravitation.*

Motion in a Potential Well

An analysis of Kepler's laws brought Newton to the conclusion that the strength of the invisible strings holding all bodies together is inversely proportional to the square of the distance between them. He called this force universal gravitation. The law of universal gravitation is applicable to all matter irrespective of colour, taste, odour, or chemical composition. The universality of gravitation explains why all planets hold to similar orbits.

Kepler, Newton, and every other inhabitant of the Earth were very lucky. The mass of the Sun exceeds hundreds of times the total mass of all the planets. This means that the effect of all the planets on the Sun is minor and may, therefore, be neglected. It is for this reason that the motions of the planets about the Sun are simple. Even so it took the human race more than a millennium to solve the riddle of epicycles and deferents. Somebody joked that if mankind had appeared on a planet in a binary, in which the planet's motions would be beyond formal description, the law of universal gravitation would never have been discovered. So binaries are not suitable as the birth places of sophisticated civilizations.

The problem is easier in our Solar System. The planets are kept in their orbits by the Sun. The attraction between the planets is insignificant. It is easier to tackle planetary motions in terms of energy rather than force, since the mathematics taught at school is not enough to solve the equations of motion. According to Newton's law, bodies are surrounded by a gravitational field. The field may be described by a potential U. Let us look at the physical meaning of the potential.

Suppose there is a body with a mass M (Fig. 3). To measure its gravitational field we need a *test particle*, i.e. a body whose mass is so small that its effect on the body M may be neglected. Usually we assume the mass of a test particle to be equal to unity whatever measurement units being used. Now we take a test particle and shift it from point *1* to infinity. To do this, we have to apply a certain force and do some work on overcoming the body's gravitation.

The work done and taken with an opposite sign is termed a *potential* of the gravitational field of body M. By contrast, if a particle

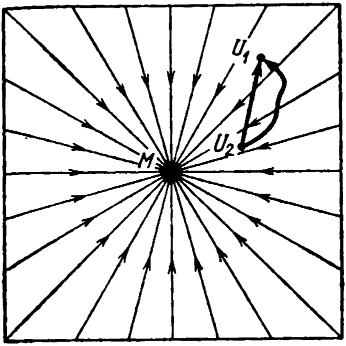


Fig. 3. The work to be done to move a test mass M in a gravitational field is equal to the difference between the potentials, $U_2 - U_1$, of the initial point and the final point and is independent of the shape of a trajectory the test mass follows

falls from infinity, the work done by the gravitational field is a potential with an opposite sign, i.e. $-U$.

The gravitational force varies only with the distance and is always directed along the straight line toward body M. This means that the potential is dependent only on the distance between the body and the particle. The work to be done to move the test mass from point *2* to point *1* is equal to the difference between potentials U_1 —

U_2. When moving freely the test particle's total energy, i.e. the sum of the kinetic energy (K) and potential energy (U), remains constant, or $K + U =$ const. The potential of point mass M is

$$U = -\frac{GM}{r}, \tag{1}$$

where G is the gravitational constant and r is the distance between the body and the

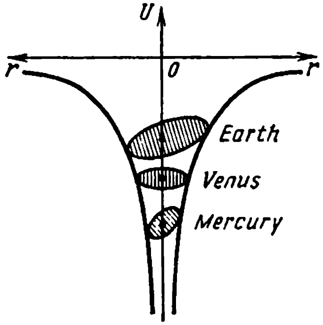


Fig. 4. The potential well around the Sun. In the coordinates U (potential) and r (distance), the orbits of the planets are ovals

particle M. It is easier to give the gravitational constant as $1/G = 1.5 \times 10^{10}$ kg·s²/m³.

Figure 4 shows qualitatively the potential of the Sun as a hyperbola. Rotating the hyperbola about the U axis yields a potential well. The idea of potential is useful because a body "placed" at some point r will "slide down" to where the potential is the smallest.

The planets of the Solar System are like test particles. Kepler and Newton treated the planets in the same way we treated test particles when they studied the Sun's gravity. (Thus we are inhabitants of a test particle called the Earth.)

How do the planets move in a potential well? In terms of the coordinates $U(r)$, they move along circles (if the orbits are circular) or ovals (not ellipses!). You may ask why the planets don't "slide" to the well's bottom. The reason is because they possess angular momentum caused by their orbital motions. The planets move without friction and therefore their angular momentum is everlasting. This, however, is not the only type of motion possible in a potential well. We mentioned above that if we place a test particle on the side of the well, it will slide to the centre, i.e. fall into the Sun. If, however, we push it strongly, it may fly away to infinity; we have given it a velocity in excess of the solar escape velocity. The reason that the only celestial motions we observe today are ellipses is that everything else that was doomed to leave the Solar System or fall into the Sun did so a long time ago.

It can be shown that all the possible trajectories inside a potential well may be obtained using a cone and a plane. By cutting a cone with a plane, we obtain

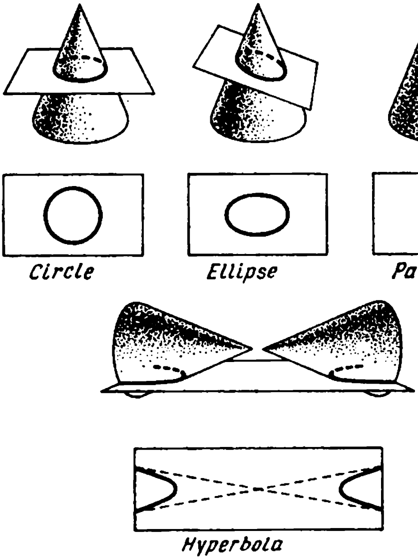


Fig. 5. Various conic sections

three types of curves (Fig. 5): (a) a circle or an ellipse; (b) a parabola; and (c) a hyperbola.

There are four curves but three types.* There is an explanation for this. A circle

* A straight line is also possible. This degenerate case occurs if a test particle does not possess angular momentum. The total energy in this case may have any sign.

and an ellipse correspond to closed motion in which the sum of the kinetic and potential energies is negative. For a parabola, the sum is zero: $K + U = 0$. Finally, a hyperbola corresponds to positive total energy. If, say, the Solar System is visited

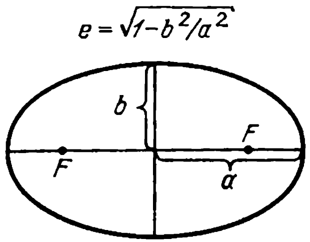


Fig. 6. Illustration of an ellipse's eccentricity

by an interstellar spacecraft, it will follow a hyperbola until the crew switch on the engines to satisfy the inequality $K + U < 0$, which is indispensable for contact.

Now let us return to the planets. An important parameter of a planet's elliptical orbit is its eccentricity, which is a measure of its oblateness (Fig. 6). The more oblate an ellipse, the higher its eccentricity is, and the closer it is to unity. A circle is in fact an ellipse with zero eccentricity. The Earth's eccentricity is $e = 0.017$, and it is closest to the Sun in winter in the Northern hemisphere and farthest from it in summer. This difference is not, however, big enough to produce a noticeable effect on the change of seasons, which is mainly caused by the relative position of the Earth's axis with respect to the Sun.

Kepler's first law is a special result of the law of universal gravitation. If gravity were not subject to the inverse-square law, the orbits of test particles would not be ellipses and might not even be closed, which means that having left one point a particle would not follow the same path a second time. Periodic motion is a phenomenon brought about by forces which are inversely proportional to the square of the distance.*

Kepler's second law results from the conservation of the test particle's angular momentum in the gravitational field of a point mass. Indeed, gravity is always directed along the line connecting the test particle and the central body. The angular momentum is determined by the velocity component perpendicular to the radius-vector; this momentum is not changed by gravity. The same can be said about any central force field.

Kepler's third law may be formulated in the following way:

$$\frac{a^3}{P^2} = \frac{G}{4\pi^2} M_{\odot},$$

* This is also typical of a body moving in a field of force proportional to distance, e.g. the rotation of a weight tied to an elastic string.

where P is the planet's period of revolution about the Sun, $M_{\odot} = 2 \times 10^{30}$ kg is the mass of the Sun, and a is the semimajor axis of the ellipse. For circular orbits, this pattern may be determined by every school pupil provided it is not forgotten that the semimajor axis of a circle is its radius.

You may wonder why I have spent so much time discussing motion about the Sun instead of binary stars since in a binary the masses of the stars may be comparable and the above conclusions may not be relevant. The surprising thing, however, is that everything we have discussed is useful for the binaries too.

About the Centre of Mass

A binary's components can hardly be called test particles and the motion of one star is determined by the position of its companion. Both revolve about each other. We know (don't we?) that in a closed system the centre of mass must either stay where it is or move uniformly. The effect on the system of other stars is insignificant. Both stars move in the same manner as the planets in the Solar System, i.e. along ellipses at one focus of which lies the binary's centre of mass (Fig. 7). These ellipses are termed the stars' absolute orbits. The name reflects the fact that these orbits are constructed in the system of a binary's centre of mass.

The elliptical shape of the orbits of binary stars has been proved by direct observations

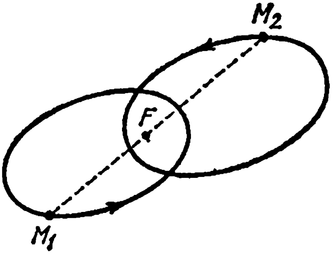


Fig. 7. The stars' absolute orbits in a binary

of our nearest binaries (Fig. 8). Astronomers, though, find it easier to calculate a relative orbit.

Here the general practice is to assume that one of the two stars is stationary and to measure the position of the second one with respect to its stationary companion. The apparent orbit is the projection of the true relative orbit on the celestial sphere. It is also an ellipse. (If you think about it, you will see that if a projection of a circle is an ellipse, then a projection of an ellipse is an ellipse too.) The foci of the apparent and true ellipses do not coincide. For this reason the stationary star in Fig. 8 stays beyond the axis of the apparent orbit.

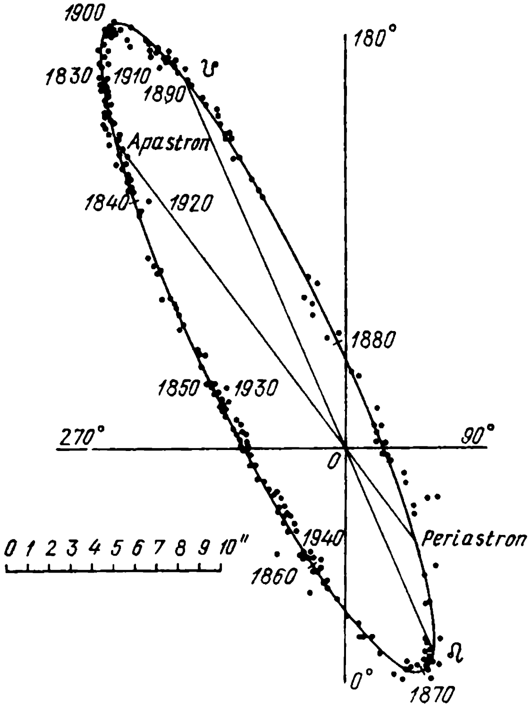


Fig. 8. The apparent orbit of a star in the binary system of α Centauri. This is our closest binary, therefore its orbit's shape can be plotted from direct observations. The bright star is at point O, the position of its companion is shown by dots. (The observations were conducted in 1830-1940. The scale is seconds of arc.)

In a star's motion along an ellipse, Kepler's second law remains valid, but his third law is slightly changed. In the formula involving the orbit's period and size, star masses must both be present, viz.

$$\frac{a^3}{P^2}=\frac{G}{4\pi^2}(M_1+M_2). \quad (2)$$

If M_2 is much smaller than M_1 ($M_2 \ll M_1$), then M_2 may be neglected and we get Kepler's third law for planets.

The point on the orbit where the stars are closest together is called the *periastron* and the point at which they are farthest apart is called the *apastron.** These two points are connected by the major axis or the *line of apsides.***

Who's Chief in a Binary?

Which of the two stars in a binary is the dominant one when considering orbital motion? A naive student of astronomy may decide it is the more massive partner, supporting the conclusion by taking the limit as the mass of one of the stars tends to zero.

* Periastron and apastron stem from the Greek words *peri* meaning near and *apo* meaning away from; and *astron* meaning star.

** The line of apsides (*absis* means an arch in Latin) is the line connecting the point of closest approach and the point of farthest retreat.

In reality, this is wrong and the situation is not that simple.

An orbital motion in the centre-of-mass system is described by three mechanical quantities. First, each of the stars has a momentum, M_1v_1 and M_2v_2. Second, each has a kinetic energy, $M_1v_1^2/2$ and $M_2v_2^2/2$. Third, you should not forget about the angular momentum. For circular motions, the latter may easily be calculated: $M_1v_1r_1$ and $M_2v_2r_2$, where r_1 and r_2 are the distances between the binary's centre of mass and the stars. Each parameter is important.

Now let us compare the stars in terms of these parameters (Table 1). Let $M_1 > M_2$.

Table 1

Parameter (absolute value)	More massive companion	Less massive companion	Which is more important?
Momentum	M_1v_1	M_2v_2	equal
Kinetic energy	$M_1v_1^2/2$	$M_2v_2^2/2$	the smaller star
Angular momentum	$M_1v_1r_1$	$M_2v_2r_2$	the smaller star

In the centre-of-mass system the binary's total momentum must be zero. It follows that the absolute values of the stars' momenta are equal (but having opposite signs). Now let us compare the energies. Since the momenta are equal, the ratio between the kinetic energy of the more massive star and that of the smaller one is clearly equal to the ratio of their orbital velocities. It follows from the equality of the momenta that $v_1/v_2 = M_2/M_1$, i.e. the kinetic energy of the less massive star is higher!

The same thing is true of the angular momentum. By dividing the angular momentum of the more massive star by the angular momentum of its less massive companion, we get r_1/r_2, that is M_2/M_1, which is less than one. Now you can see that in a binary the smaller star is chief.

Let Us Determine the Orbit of a Binary

It is clear that in order to describe an orbit you need quantities independent of time. Here we shall rely on the conservation laws, which determine quantities that are constant over time.

First, a binary's energy is conserved because it is a closed system. Second, the total momentum of the two stars is conserved. Third, the angular momentum associated with the orbital motion is constant. Note that we can afford to neglect the size, temperature, luminosity, etc. of the stars, as the orbital motion of the stars is independent of them.

If the orbits are not circular, there is another invariant, namely, the direction of the line of apsides.

Let us count the quantities we need to determine an orbit. We do this in a reference frame whose origin is at the binary's centre of mass. The angular momentum of a binary is a vector perpendicular to the orbital plane of the stars. It means that by specifying the angular momentum we automatically specify the orientation of the orbital plane. A vector is specified by three scalar quantities and so the orbital plane is determined by the same number of quantities. Yet we are still far from a complete specification of an orbit. An ellipse may rotate in this plane by changing the direction of the major axis (the line of apsides). Consequently, we need two more quantities which determine the direction of the line of apsides. All in all, we have five parameters. Having specified them, we can fix the orbit in space, but so far we have said nothing about its size or oblateness. That adds two more parameters. Thus a complete specification of an orbit requires seven parameters. We could use the binary's total energy (one parameter), the total angular momentum (three parameters), a vector in the direction of the line of apsides (three parameters though only two of them independent), and the eccentricity. This combination, however, is not the best one because the energy and the angular momentum cannot be directly observed.

In practice, the following parameters are used: the masses of the stars, M_1 and M_2; the semimajor axis a or the period of the binary, P (these are related through

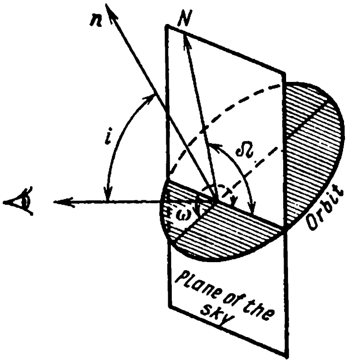


Fig. 9. A star's orbital parameters in a binary

the masses by Kepler's third law); the eccentricity e; the angle i of the orbital plane to the plane of the sky (the one perpendicular to the line of sight); the angle between the line of intersection between the orbital plane and the plane of the sky (the nodal line) and the line of apsides, ω; and finally the position angle Ω (Fig. 9). In this figure, N is the direction to the North celestial pole and **n** is the vector along the normal to the orbital plane. These seven parameters are conserved in Newtonian mechanics and these are the ones determined by researchers when studying binaries. In order to describe stars' motions along an orbit, we must also specify the position of the stars at a particular moment.

Test Particles in a Binary

We now look to see what the orbits of the planets in the Solar System would be like if the Sun were accompanied by another star with comparable mass. One potential well is now supplemented by another. Clearly, the system is far more complicated and calculating these orbits would have been a riddle for Kepler himself.

It is easier to study the motions of test particles in the gravitational field of a binary star in a reference frame which rigidly rotates with the stars. The origin of the frame coincides with the centre of mass, the x axis is directed along the line connecting the stars, the y axis lies in the orbital plane, and the z axis is perpendicular to the plane (Fig. 10). Thus the rotation may be ignored. However, as soon as we get rid of rotation of the stars, we have to deal with the centrifugal force which appears in any noninertial reference frame. But this is a minor headache. In a system with the stars moving in circular orbits, the angular velocity of the star does not vary with time. The forces attracting a test particle will depend only on the particle's position and will be independent of time. This allows us to introduce a potential.

In celestial mechanics, this is called a restricted three-body problem. It is re-

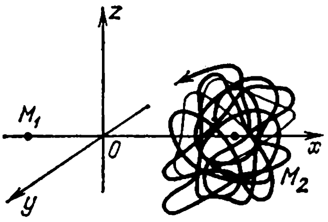
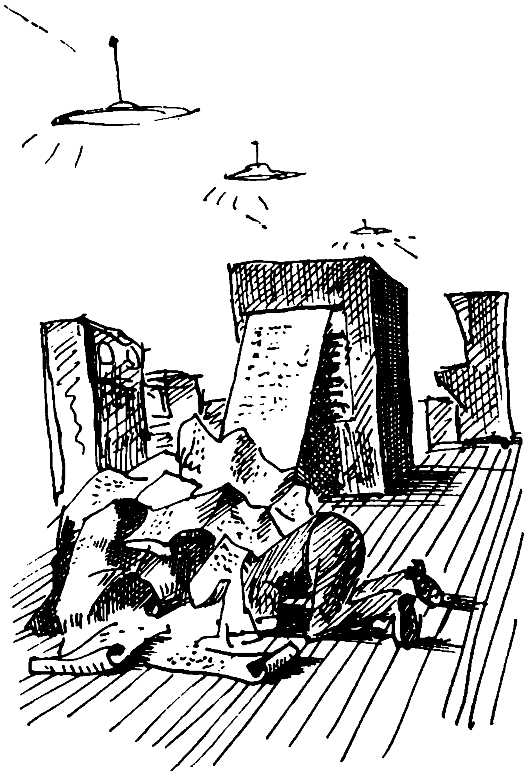


Fig. 10. The motion of a test particle around one of the stars

stricted because the third body, i.e. the test particle, does not affect the motion of its two companions. In the general case, the trajectory of a particle may only be calculated numerically and its shape will resemble that in Fig. 10. By changing the initial coordinates and velocity of the particle, we can obtain a great many trajectories of this kind. I say "many" and I mean it. The best computers now available may reduce the time needed to calculate orbits, but get us into trouble because we would drown in the flood of paper produced by the printer.



Luckily, we don't need computers and the motions of a test particle may be studied qualitatively. The trajectory of an individual particle is not important because its complexity makes the exercise useless. What we want is to see what happens to the particle. Such an analysis was first accomplished by the American astronomer and mathematician George Hill at the end of the last century.

Let a test particle be influenced by three forces: the gravity of the two stars M_1 and M_2, and a centrifugal force. All these forces are potential and may be described by a single effective potential U. Now let us see what happens to a particle moving in the binary's orbital plane. All the forces act in the same plane, so the test particle must stay within the plane too.

The behaviour of the potential U is shown qualitatively in Fig. 11. Here the plot shows three peaks separated by wells where the stars are located. You will notice three special points. If we carefully put a test particle atop any of the peaks, they will be in equilibrium. Unstable, but it is an equilibrium! These points were first discovered by the great French scientist Louis Lagrange in 1772.

Surfaces over which the gravitational field is constant are called equipotential surfaces. We can obtain them by cutting the potential by planes parallel to the x and y axes (Fig. 11). Their projections on the xy plane are shown in Fig. 11. Unfortunately, it is not easy to follow the behaviour of the potential in the xy plane. We must keep in mind that the potential grows when moving away from the x axis and along the y axis. It follows that points L_1, L_2, and L_3 are, probably, passes rather

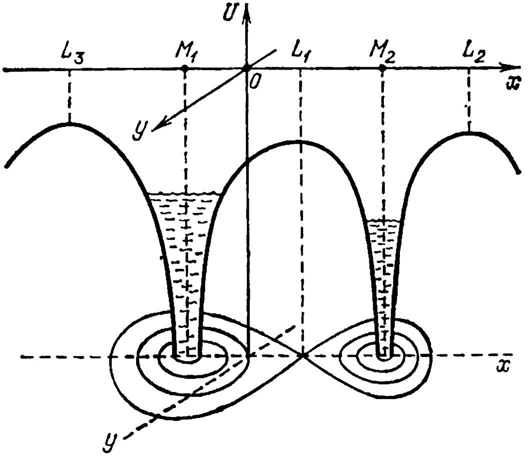


Fig. 11. The behaviour of an effective potential in a binary

than peaks (Fig. 12). An attentive reader will notice that if the potential grows when moving away from points L_1, L_2, and L_3 and is small again at infinity, there must be peaks somewhere. And right he is. These peaks correspond to two more Lagrangian points, otherwise known as libration points. They will be discussed below.

As it moves, the test particle's total energy, i.e. a sum of its kinetic energy K and potential energy U, remains constant:

$$K + U = E \quad \text{const.}$$

Suppose we make a thought experiment. We shall throw a particle from the stars. It is obvious that if we give the particle a

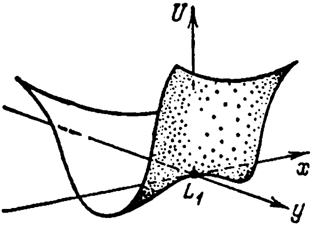


Fig. 12. The behaviour of a potential near the inner Lagrangian point (a saddle)

push, it will first go up the well and then will fall down it again. When it is farthest from the star, the particle halts and its kinetic energy becomes zero: $K \quad 0$. This means that at this moment the particle's total energy E is equal to the potential at the turning point. It is clear that the particle can only move when $U \leqslant E$. By passing a section through the potential along the line $U \quad E$, we find the area within which a particle with energy E can move. In three-dimensional space we get equipotential surfaces instead of lines. Hence, if we know a particle's energy, we can specify the area within which it can move. Figure 13 shows a view of an equipotential surface in the binary's orbital plane. When the energy is small, the area of the particle's

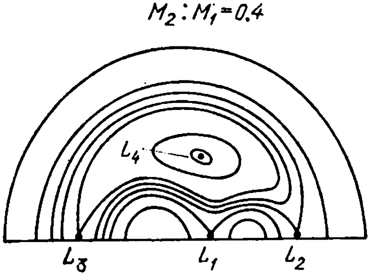


Fig. 13. Equipotential lines in a binary's orbital plane. The ratio of the stellar masses is 0.4

motion is small too. By "launching" particles with increasing speed we increase their energy and enable them to travel farther. When the energy reaches a certain value, the areas meet at the Lagrangian point L_1 making a surface which looks like figure of eight. In memory of the French astronomer and mathematician Edouard Roche, it is called a Roche lobe.

If a test particle finds itself at point L_1, it can reach the neighbouring star without a loss of energy. Particles with great energies can go beyond the Roche lobe for they no longer belong to a single star. The resultant of all the forces acting on a test particle is zero at Lagrangian points. We may use this fact to find the position of these points. The solution is simplest when the stars are of equal mass. We suggest you solve this problem on your own.

For an eccentric orbit, the motion of a test particle cannot be described by a potential function and we can no longer assume that a particle with some energy will necessarily move in the vicinity of one star. True, we can calculate the particle's trajectory using a computer, but a qualitative analysis is impossible.

Stars' Shape

A student who was to speak about the interior of a star but who had only a vague idea of the subject began by saying, "Well, a star is a hot gaseous sphere. The formula for the area of the surface of a sphere is $S = 4\pi r^2$ and that for the volume..."

The student was right in saying that single stars are spherical, the reason being that this is energetically favourable. Star's matter, like a fluid, will fill any vessel into which it is poured and its surface will be an equipotential one. The star itself creates the field which forms its matter. I have already said that the potential of a point mass is inversely proportional to distance (formula (1)) and at the point $r = 0$ the potential is at “minus infinity”. Such a situation is impossible in nature, at least in ordinary stars. The potential of a star is more like a wineglass without a stem

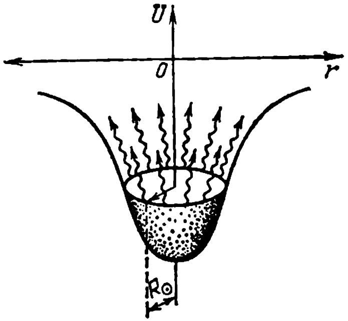


Fig. 14. A star’s gravitational potential does not go to “minus infinity”

(Fig. 14). If $r = 0$, the potential is small, yet finite. On the surface $r =$ const, i.e. the star is a sphere.

Now let us look at the shapes of stars in a binary system. Imagine the binary’s potential well is filled with a fluid, as we did for a single star (see Fig. 11). The fluid spreads out so that the star’s surface is an equipotential one. The star will stretch along the line connecting the binary’s components.

You see, the problem is not as hard a nut to crack as you might imagine. Yet in the 18th century the argument on another, more simple, issue was so heated that a special Arctic expedition was organized. The story of this endeavour is told by the outstanding

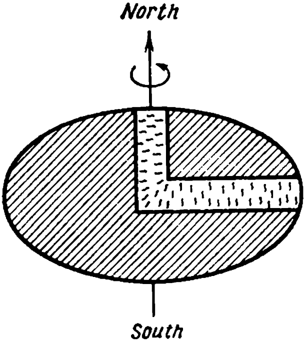


Fig. 15. Newton's thought experiment

astrophysicist Subrahmanyan Chandrasekhar in his monograph about stars' shapes.

In 1687, Isaac Newton published his famous *Principia*. In it, he explained Kepler's laws by the law of universal gravitation and answered many other special questions. One concerned the Earth's shape. Newton believed that our planet is flattened at the poles due to its rotation. To prove his hypothesis he showed his wit. Suppose, he suggested, we dig two wells leading to the Earth's centre (Fig. 15), one along the rotation axis, the other in the plane of the equator and fill the wells with water. In order for the water to stay in equilibrium and not splash out, the weight of the water in the both wells must be the same. But a body's weight is its mass times the effective acceleration, the latter being the difference between the acceleration due to gravity and the acceleration due to the centrifugal forces. At the equator, the acceleration due to gravity would be slightly reduced by the centrifugal acceleration. In order for the water weight in the equatorial and polar wells to be the same, the water level in the equatorial well must be higher.

This conclusion, however, ran counter to contemporary astronomical data. The famous French astronomer Dominique Cassini had measured the meridian arc lying within France and considered that his data demonstrated that the Earth was stretched along the poles. It was difficult to argue with a man who was the first director of the Paris observatory and the discoverer of four of Saturn's satellites and the famous dark division (Cassini division) in Saturn's rings.

Who Was Right?

Several generations of Cassini's and Newton's successors kept up the argument. Only in 1738 a special expedition led by the

French scientist Pierre Maupertuis went to Lapland and discovered that Newton was correct. Voltaire taunted the Arctic voyagers, asking why they had to go to Lapland to learn what Newton had known without looking out of his window.

You don't have to go to the Arctic to learn what a star looks like. What you do need is a telescope. Like the Earth, a star in a binary system is also oblate. Qualitatively, the situation is the same but in a binary things are complicated by the stars' motion about their centre of mass, which does not coincide with the stars' centres. Besides, a star in a binary system is attracted by the nonuniform gravity from its neighbour. We have already seen that the equipotential surface is a spot where the velocity of a particle with a specified energy turns to zero. In order for a surface to be an equipotential one, the star must be fixed in a rotating reference frame. This is only possible when the star's period of rotation equals the binary's period. The astronomers then say that the star rotates synchronously.

Figure 16 illustrates the shape of a star in a binary system. When it is small in comparison with the size of the Roche lobe, it looks like a triaxial ellipsoid or, say, a Central Asia melon (Fig. 16*a*). Strictly speaking, this is not true because the star's shape is asymmetric. This is more obvious when the size of a star is comparable with the size of the Roche lobe.

A star filling the Roche lobe looks different (Fig. 16*b*). In such a star a "spout" appears near the inner Lagrangian point

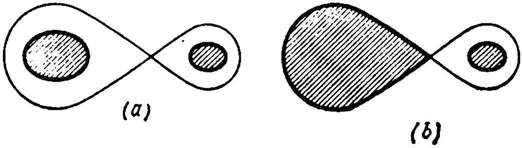


Fig. 16. The shape of the stars in a binary

and matter may be transferred through this "spout" to its companion without any loss of energy.

This is a surprising and remarkable feature of a binary star. At first sight, one might think this is abstract situation and why the star should be as large as a Roche lobe. In nature, however, nearly all binary systems sooner or later turn into such "freaks".

Formation of Binaries

The history of a star begins with its condensation out of gas and dust due to gravitational instabilities. This idea was first applied to the Sun by Immanuel Kant in 1755 and was later supported by Pierre Laplace. The birth of a star is hidden under "a veil" but has nothing to do with "devilry". The "veil" is a result of the opacity of the contracting cloud of gas to electromagnetic waves. You may still run into an opponent of this hypothesis who will point out that, while no astronomer has ever seen a contracting gas cloud, explosions may be seen every day. Here the strong influence of selection is at work. Stars are born where there is a great deal of gas and dust, namely, where the visibility is worst.

A rigorous mathematical explanation as to what contracts a cloud of gas was provided by the English astronomer James Jeans at the beginning of the 20th century. Let us suppose that an infinite space is filled with a homogeneous gas and perturb the gas parameters in some limited area, for example, by slightly compressing the gas. If there were no gravitation, the compression would be followed by an expansion perturbing neighbouring areas of gas. A wave of perturbations (sound) would run through the gas. In interstellar space, gas clouds are of great size, and gravitational forces become as important as the forces of pressure. Suppose we find a spherical area in the interstellar space and compress it a little. The force with which the cloud attracts itself is proportional to GM^2/R^2, where M and R are the mass and the radius of the cloud respectively. External forces are ignored for they compensate each other.

Hence, the pressure of the gravitational force is proportional to $(\rho R)^2$.* The pressure of an adiabatically compressed monatomic gas depends on the density as $P \propto \rho^{5/3}$. From this it follows that for very large clouds (at some R) the gravitational force will exceed the force of the gas pressure and the cloud will start contracting. This process is referred to as *Jeans instability*.

The minimum size from which a cloud becomes unstable with regard to compression is termed the Jeans radius. Approximately the Jeans radius may be found by equating the gas pressure in a sphere with radius R to the pressure of the gravitational force. The gas pressure is calculated by the equation of state for an ideal gas. We determine the pressure of the gravitational forces by dividing the sphere into two equal parts and calculating the force of attraction between the two halves. The result is

$$\rho \frac{\mathcal{R}T}{\mu} = \frac{GM^2}{4\pi R^4},$$

from which we get an approximate expression for the Jeans radius:

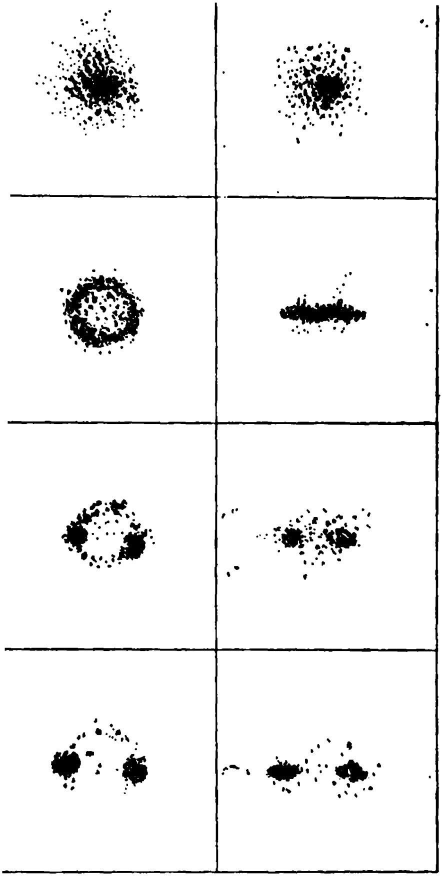
$$R_J \simeq \frac{3}{2}\sqrt{\frac{\mathcal{R}T}{\pi\mu G\rho}}.$$

* In fact, given $M = \rho R^3$, we can represent the pressure of the gravitational force as $P_{gr} \propto (GM^2/R^2)/R^2 \propto \rho^2 R^2$.

Here T is the gas temperature, $\mathcal{R}$ is the gas constant, and μ is the relative molecular mass of the gas.

Of course, the gas is not uniformly distributed throughout the Galaxy. In the late 1970s, it was discovered that almost all the gas is concentrated in gigantic molecular clouds with masses hundreds of thousands and millions times greater than that of the Sun. We might ask why a single cloud doesn't produce a single giant star. This does not happen because the clouds are also inhomogeneous and the stars are formed in the densest central parts of the clouds. Besides, the gas in the clouds is not at rest; it moves chaotically and this motion is called turbulence. Different parts of the cloud rotate in different directions. Eddies occur at all levels, from the cloud as a whole to small parts.

So binary star systems might arise due to turbulence. A computer simulation of the process is shown in Fig. 17. First the cloud is compressed along the rotation axis, and then it turns into a torus. The torus breaks into separate blobs which eventually grow into binary stars. In fact, star systems evolving in this way can contain more than two stars (multiple stars) and there are a great number of multiple stars in our Galaxy. This book is about binaries, although our discussion refers to triple systems too. The simplification is



17. This is, probably, how a binary is born of a rotating cloud. A view from the poles (left) from the equator of the rotation (right)

justified because we are interested in multiplicity only from the viewpoint of the effects the stars have on each other. Nature is such that any multiple system can be reduced in this sense to a binary. Three stars cannot coexist as equal companions. A triple system sooner or later ejects one member provided the distances between the stars are comparable. It happens due to a cumulative effect which is well-known in fluid dynamics. The effect is used in modern antitank projectiles. It can be illustrated by the Pokrovsky experiment.

Take a test tube full of water. If you let it fall several dozens of centimetres vertically onto the floor, a spout of water will rise several metres into the air (Fig. 18). It seems like the effect violates the law of energy conservation. In reality this is not so. What does happen is that the energy and momentum are redistributed in the water. Most of the water remains in the test tube and does not splash out at all; however, it gives a small portion of the water its kinetic energy, thus pushing it up much higher than the test tube initially was.

You may have come across the same effect in the underground. The designer of the automatic coin changer* must have con-

* All journeys on the underground in the USSR cost five kopecks regardless of distance. Machines are provided to give five-kopeck coin change for other denomination coins.—*Eds.*

sidered the height the coins have to fall to the collection tray. A single coin cannot jump over the wall of the collection tray because it lacks the initial potential energy. However, once in a while a coin falls to the floor. The coin has taken momentum

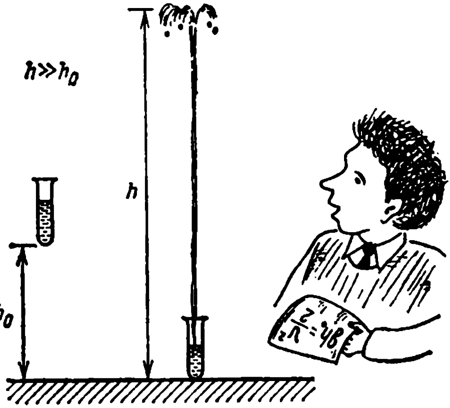


Fig. 18. The Pokrovsky experiment illustrating the cumulative effect

from its neighbours. The more coins fall at one time, the more probable it is that one will fall to the floor.

As a result of the cumulative effect, a system either becomes binary or remains triple, with one of the stars moving along an orbit such that the distance between it and the other two is much greater than the distance between the other two stars. The gravitational attraction between the two close stars is then the most important factor.

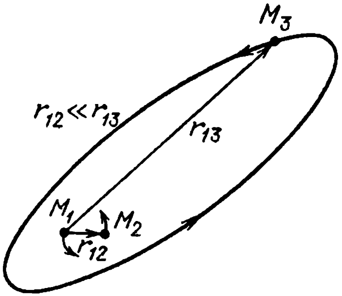
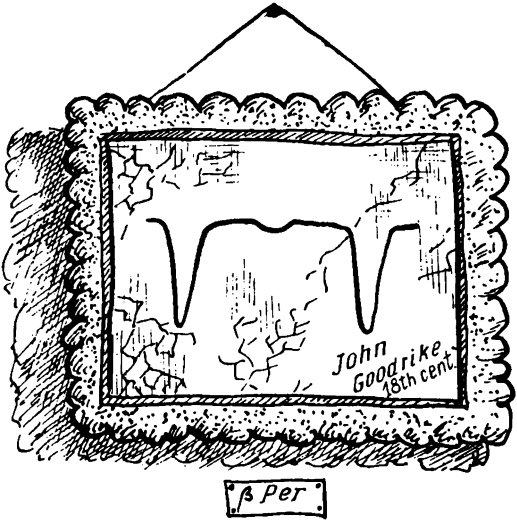


Fig. 19. As a rule, the distance between two of the stars is shorter than the distance to their third companion

For this reason multiple systems can be considered to be binaries (Fig. 19).

Chapter 2
Algol Paradox

I shall begin my story about the evolution of binary stars by telling you about a star which is well-known to any student of



A classical light curve

astronomy. This star is in the constellation Perseus and is called Algol or β Persei. The fact that β Persei is a variable star was discovered by the Italian mathematician and astronomer Giovanni Montanari in 1669 and for several centuries Algol was a typical example of an eclipsing variable star. Variations in brightness similar to those characteristic of Algol have been recorded in many hundreds of other stars, making Algol a generic term for a star type. Generation after generation of astronomers observing Algol found nothing surprising about it. Then all of a sudden (I mean "sudden" historically speaking, of course) they came to realize that, although they had known all about it for ages, something was wrong. What had seemed normal now appeared both mysterious and surprising. When you have no knowledge, you are never surprised. Astronomers had been scrutinizing the laws governing star life when they realized that an Algol-type star could not exist because it violated the laws they had so thoroughly studied. Like any true paradox, the Algol paradox proved exceptionally helpful and it became a key to the mystery of binary star evolution. To convince the reader that this is so, I shall have to start from the very beginning.

Whose Light Is "Louder"?

In astronomy, a star's brightness is measured in dimensionless magnitudes. Magnitude is introduced by choosing a reference star whose brightness corresponds to the zeroth magnitude ($m = 0$). The brightness of any other star is then given by

$$m = -2.5 \log \frac{F}{F_0}, \tag{3}$$

where F and F_0 are the brightnesses of stars of the mth and zeroth magnitudes respectively. Usually the energy of a star is characterized by its luminosity, i.e. the amount of light falling from the star per unit area per unit time. It follows from the definition of magnitude that a star of the 5th magnitude is 100 times weaker than a zeroth magnitude star.

You may wonder what point there is in having magnitudes if there is a physical characteristic such as luminosity. We need magnitudes because the luminosities of stars vary very widely. For example, the brightest star, i.e. the Sun, and the weakest star visible to the naked eye differ in brightness by a factor of more than 10^{12}. In terms of magnitudes, this corresponds to slightly more than 30^m, which is much easier to handle.

Nature took this into account when it designed a human eye. It provided us with a sort of a "computer" which can take logs. In physiology, this computer is called the Weber-Fechner law: our sensations grow in arithmetic progression when stimulation increases in geometric progression. The same thing happens with our ears. It is because of the Weber-Fechner law that sound intensity is measured in decibels. True, in contrast to magnitude, the definition of a decibel contains a factor of 10 in front of the sound intensity logarithm instead of -2.5. In principle, however, there is no difference between magnitudes and decibels. If you like, you could measure sound intensity in magnitudes and star brightness in decibels. However, magnitudes have been used in astronomy since Hipparchus (2nd cent. B.C.). To get some idea of the brightness of a zeroth magnitude star look at Vega in summer. Its magnitude is close to the standard one: $m = 0.14$.

Now back to Algol.

Light Curve

Late in the 18th century, the English amateur astronomer John Goodrike first noticed the strictly periodic variations in Algol's magnitude. The variation occurs with a period of 2 days, 20 hours, 49 minutes. A periodic process is best described by a *phase*. A phase is a time expressed in parts of period P. In practice, the phase is calculated by assuming that at some moment in time the phase is zero. In star observations, the initial moment (or zero-phase time) is when a star's brightness is at a minimum. Then the observation time minus the initial moment is divided by the period. The fractional remainder is called the phase. The brightness of a variable star is usually measured by comparing it to a nearby constant star. A graph of brightness against a phase is called a light curve.

Algol's light curve, as discovered by Goodrike, has two minima per period: a

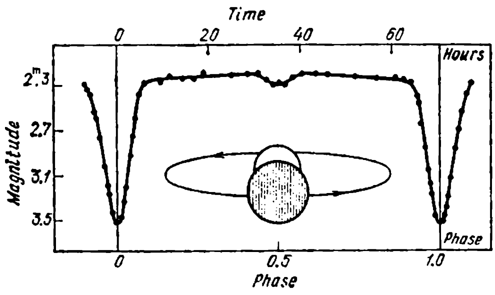


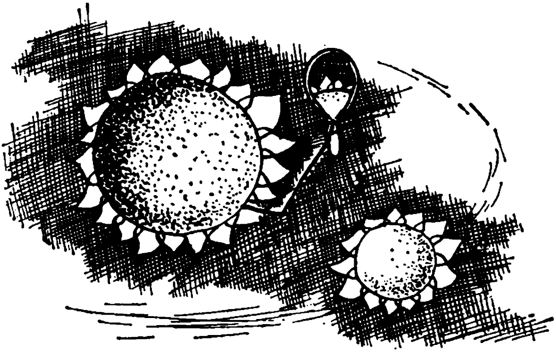
Fig. 20. Algol's light curve

"deep" primary minimum at phase zero and a "shallow" secondary minimum at phase 0.5 (Fig. 20). We can understand this light curve pattern only by assuming that Algol is a binary. (The phenomenon is illustrated in Fig. 20.) Algol's components revolve about each other with a period of 2.9 days; thus the two stars periodically eclipse each other. True, they only do so partially. A question arises as to why one minimum is deeper than the other, because each star eclipses the same area of its companion, namely, the area of the overlap between the two circles. So what do we actually mean by the depth of an eclipse and how do we measure it? When there is no eclipse, we see both stars and the brightness of the system is the sum of the brightnesses of its two components. When one star "covers" the second one, the binary's brightness is reduced by the amount of light radiated by the eclipsed part of the star. To calculate this amount we must multiply the energy produced per unit area by the area of the eclipsed surface. It is clear that the difference in the depths of the minima is due to the difference in the amount of energy radiated per unit area of the two stars. As a first approximation, we may assume that the stars radiate energy like blackbodies. The latter may be represented by any body with constant temperature. Blackbodies are described by the Stefan-Boltzmann law, according to which the radiation from unit area is proportional to the fourth power of the body's absolute temperature:

$$F = \sigma T^4.$$

Here $\sigma = 5.67 \times 10^{-8}\ \mathrm{J \cdot m^{-2} \cdot K^{-4} \cdot s^{-1}}$, which is the Stefan-Boltzmann constant. In fact, we need this law only to say a very simple thing: the hotter the body, the brighter it is. Now one thing is certain: Algol is composed of two stars with different temperatures and at the zero phase the hotter star is eclipsed.

Algol-type light curves are characteristic of variable stars and we know of several thousands of such stars. In each case, there are two minima with nearly constant brightness between them. Why do we have to say "nearly" constant? Since we see two whole stars between the eclipses and the system's brightness is the sum of the stars' brightnesses, one might think that the light curve must stay constant. However, after the



Reflection effect

primary minimum the system's brightness slowly rises until phase 0.5 and, but for the second eclipse, there would be a maximum here (see Fig. 20).

The growing brightness is explained by the reflection effect. Keep in mind that one of Algol's stars is hotter than the other. The hotter star illuminates the closer side of the colder star and thus makes it a little brighter. It is as if the hot star is reflected in its colder companion. In fact, we have here a case of reemission with a change in the wavelength of light. By the way, the reflection of visible light in a mirror is also reemission. Here the light is reemitted by the electrons in the thin layer of metal deposited on the glass. However, in the process the wavelength remains constant. If you see redhair in the mirror, then you definitely have redhair.

Let us once more follow the phase dependence of the reflection effect. At phase zero, the colder star eclipses the hotter one. This means we are seeing the near and colder side of the darker star. Later in the orbit (increasing phase), we see more and more of the illuminated side of the colder star and the whole system slowly becomes brighter. By phase 0.5 we see the hottest part of the colder star. Now the reflection effect is at a maximum. Then the system's brightness symmetrically falls to phase one. In the Algol system, the reflection effect is small and insignificant, the eclipses being really important. Now imagine a system in which its components do not eclipse each other because either there is nothing to eclipse or nothing to eclipse with. This is quite possible. Then the reflection effect may be the only reason for variations in the brightness of a binary. Below we shall come across binary star systems in which the reflection effect is many times stronger than it is in Algol.

What Can an Algol-Type Light Curve Tell Us?

What information can be obtained from an Algol-type light curve, i.e. the one consisting of two minima? Suppose we observe a binary system edgewise, and our line of sight lies in the orbital plane (Fig. 21). For simplicity let the orbit be circular. In

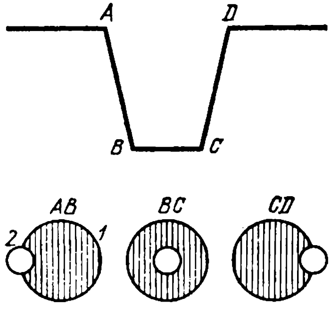


Fig. 21. A central eclipse

this case, eclipses will be central and one of the components will be wholly eclipsed. The binary's plane is at an angle $i = 90°$ to the plane of the sky. Then the light curve will be trapezoid-shaped. Let brighter star *1* be the larger. At the primary minimum, the brighter and larger star is eclipsed. The side *AB* of the trapezoid shows the star being gradually covered by star *2*. At point *B* the edges of stars *1* and *2* touch (an internal contact) and while star *2* "travels across" the disk of star *1*, the system's brightness remains the same. Side *CD* corresponds to star *1* gradually appearing from behind star *2*. Side *CD* is proportional to the radius of star *2*. The duration of the eclipse (from *A* to *D*) is proportional to the sum of the stars' sizes, and the duration of the flat bottom *BC* is proportional to the difference between the stars' sizes. We have two equations and two unknowns. Thus the light curve makes it possible to calculate star radii. You may wonder how we can measure time and obtain distance. We are also supposed to know velocity from the light curve. Truly, we cannot determine star size. We can, however, determine it in units of the radius of the binary's orbit (a). It takes the star a period to travel $2\pi a$. Since we know the period, we may learn what fraction of the orbit's total length is covered by the star during the eclipse.

If the line of sight does not lie in the binary's orbital plane, the duration and kind of eclipse will be determined both by the relative stars' sizes and by angle i. The shape of the light curve will also be different. At a certain angle, the smaller star is not wholly eclipsed, which means there will not be a flat bottom in the secondary eclipse. The form of eclipse allows us to determine the angle at which a binary's orbital plane is inclined. At a small angle i,

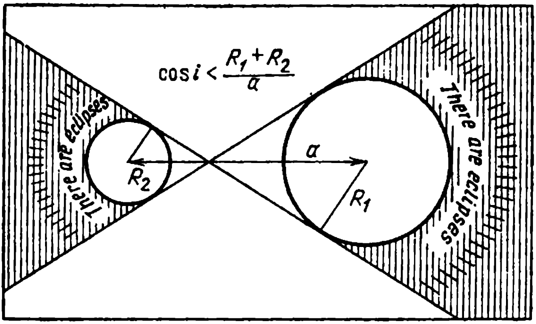


Fig. 22. Are there eclipses?

there might be no eclipse at all. The minimum angle can be obtained geometrically from the relative sizes of the binary's components (Fig. 22).

The light curve thus permits us to determine a binary's period and the relative sizes of the stars. So now let us discuss how we measure the absolute dimensions and, more important, the masses of the stars. What magic "ruler" could be put beside the binary's orbit and stars? Nature has taken pains to place such a ruler inside every atom whether it is on the Earth or in a distant galaxy.

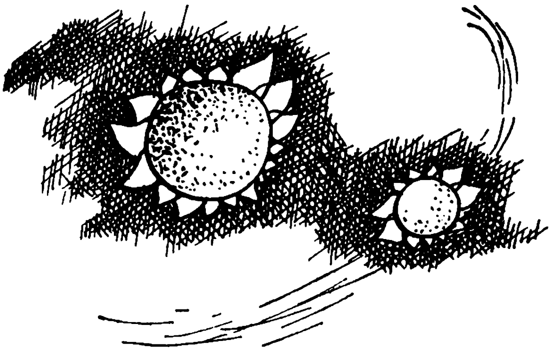
Doppler Effect

Accounts of the Doppler effect often begin with a joke about a physicist who drove his car past red traffic light. He tried to explain to the policeman who stopped him that he had mistaken a red light for a green one because of the Doppler effect. The policeman, however, knew some physics too and booked the physicist for speeding. It seems like the joke was duly appreciated by the traffic police as they use now a speed-gun based on the Doppler effect. Now we shall see how it operates.

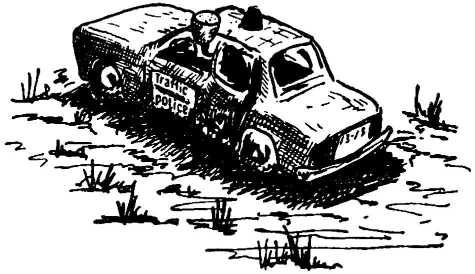
Suppose we have a source and a receiver of periodic pulses. If the source is at rest, the period of the signal arriving at the receiver will not be changed and will equal P_{source}. Now suppose the source is either approaching or departing from the receiver at a speed v. During the period P_{source} the source will cover a distance vP_{source}. This means that the next pulse will have to travel a shorter (longer) distance. The pulse will arrive earlier (later) by the time in which the signal travels the length of the source's shift, i.e. vP_{source}/c, where c is the signal's speed. The period of the signals arriving at the receiver will change by

$P = P_{\text{rec}} - P_{\text{source}} = \Delta P$. In fact, this relative change in period is what we call the Doppler effect:

$$\Delta P / P_{\text{source}} = v/c. \tag{4}$$



By comparing the periods of the transmitted and the received signals, we can obtain



the speed at which the source is either moving away or towards the receiver. The police's speed-gun is both a source and a receiver. It both illuminates vehicles and picks up the echo. This makes it easy to determine the speed because P_{source} is known.

The Doppler effect is used in astronomy to measure velocities. The light coming from stars is electromagnetic waves, which are special objects composed of oscillating magnetic and electric fields. An astronomer works in terms of wavelengths rather than periods. Remember that a wavelength is the distance covered by a wave in one period: $\lambda = cP$. The relative change in wavelength is also determined by the ratio of the velocity of the light source to the velocity of light. The Doppler effect depends solely on the component of the source's velocity along the line of sight. This component is termed the radial velocity v_{rad}:

$$\frac{\Delta\lambda}{\lambda_{source}} = \frac{v_{rad}}{c}. \tag{4a}$$

So how does the astronomer know the wavelength λ_{source} of the light actually radiated by a star? Star light contains a set, or spectrum, of electromagnetic waves of varying wavelength. Generally speaking, the spectrum of radiation emanating from the depths of a star to its surface (photosphere) is continuous, the amount of energy produced by a star in each wavelength varying gradually with the wavelength (Fig. 23).

We have already mentioned a blackbody, i.e. a body in thermodynamic equilibrium. To obtain a blackbody, we must wrap it in a heatproof and lightproof blanket. It is necessary for the substance and electromagnetic waves to be in thermal equilibri-

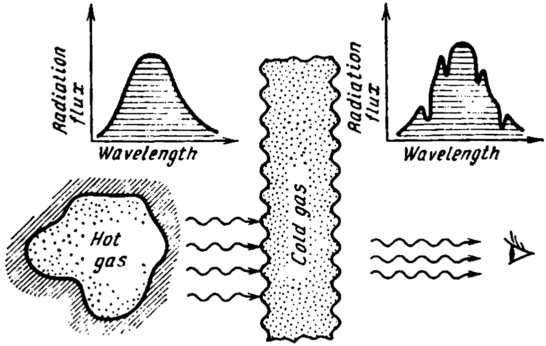


Fig. 23. The formation of absorption lines in a continuous spectrum

um, in which, on average, the energy is not transferred from the substance to the radiation and vice versa. Bodies which have the same temperature are also in thermal equilibrium and so in this sense we can speak about the temperature of radiation. A blackbody's spectrum is described by a formula derived at the turn of the 20th century by Max Planck.

Since a star's depths are very opaque, it takes electromagnetic waves a long time to be absorbed and radiated before they arrive at the star's surface. During this time the substance and the radiation come to a quasiequilibrium, and therefore the spectrum of the waves leaving the photosphere is very close to that of a blackbody. This spectrum is as regular as it is useless.

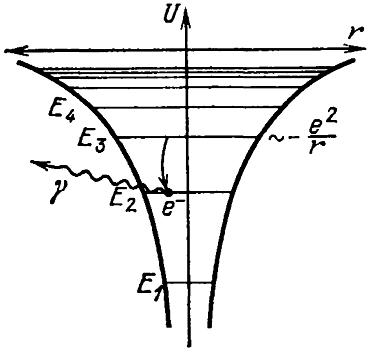


Fig. 24. An electron can have only discrete values of energy in the potential well around an atomic nucleus

If you receive such light even if its wavelength has changed due to the star's motion, it will not help you determine the star's velocity.

Fortunately, nature is not perfect and therefore things may be learnt. Stars have their own atmospheres. By definition, a star is a "hot gaseous sphere". Although hot inside, stars are surrounded by space with a temperature of —270°C. A star's atmosphere is generally colder than the star. Practically unobstructed, radiation passes through the atmosphere and thus does not have enough time for attaining equilibrium with it. This "spoils" the spectrum with irregular spectral lines.

You must bear in mind that light is not only an electromagnetic wave but also a particle. Light is absorbed and emitted in discrete bundles called quanta. Every atom can emit quanta of a particular wavelength. Each quantum corresponds to a transition of an electron from one discrete level to another (Fig. 24). Max Planck proved that each quantum's energy is determined only by its wavelength:

$$E = h\frac{c}{\lambda}, \qquad (5)$$

where h is 6.63×10^{-34} J·s (the Planck constant). For example, a green quantum has energy of approximately 2.5 eV. (1 electronvolt (eV) is the amount of energy acquired by an electron when it passes through a potential difference of 1 volt.) The atoms of a star's atmosphere, which is colder than the star itself, only absorb quanta corresponding to certain energy transitions, i.e. certain wavelengths. As a result, in the star's spectrum there will be a lack of light at some wavelengths, and we get dark absorption lines. When we said a "cold atmosphere" we somewhat simplified the situation. In fact, stars have no solid surface, and, therefore, they do not have what we would call an atmosphere. The atmosphere of a star is that layer of it in which spectral irregularities (lines) are formed. The shape of the spectral lines varies with the temperature of the atmosphere at different depths. If the temperature is lower in the layers closest to the observer, then dark absorption lines appear. The reverse of a dark-line spectrum is a bright-line, or an emission, spectrum. In the overwhelming majority of stars the temperature in the outer layers first falls and then again rises. A rise starts in a layer where the density of substance is small and quanta pass freely to the observer. This means that in most cases the optical spectrum of a star has dark absorption lines.

The wavelength of a line is governed solely by the laws of electron-nucleus interaction. These laws are the same everywhere in the Universe and so by measuring the wavelengths of the quanta emitted or absorbed by a particular chemical element we can find λ_{rad}. Then comparing the star's spectrum with a laboratory spectrum permits us to calculate the star velocity.

Radial Velocity Curve

In practice, a star's spectrum is obtained by placing at the focus of a telescope a spectrograph, that is, an instrument which splits the light like a prism but much better.

The telescope is needed to collect more light from a faint star. The spectrum is either photographed or recorded digitally and stored in a computer memory. The star's spectrum can then be compared with a laboratory spectrum of a chemical element.

We can find the velocities of binary stars by taking their spectra at different moments and orbital phases. A velocity-phase curve is called the radial velocity curve. The projection of a star velocity on a line of sight varies periodically as the star moves along its orbit. Note that in a binary the variations occur strictly in antiphase. The spectra show the lines of the components "moving" in antiphase (Fig. 25).

Consider the simple case of circular orbits. Suppose the plane of the binary lies along the line of sight (see Fig. 25). We assume that star *1* is hotter and more massive. At the time of the primary minimum the projection of the orbital velocity on the line of sight is zero. Then star *1* starts approaching us, while star *2* starts moving away. The first star thus has a negative speed and the second a positive speed.

Radial velocity curves are thus like two sinusoids in antiphase. The amplitudes of the sinusoids are the orbital velocities. However, sometimes the sinusoids meet off the x axis.

In this case, the system is moving as a whole with respect to us. The velocity at

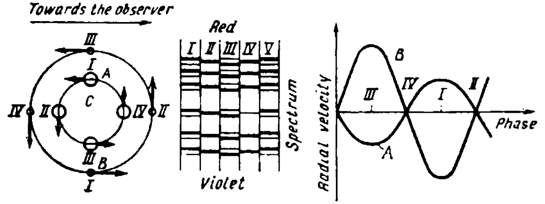


Fig. 25. A periodic "moving" of lines in a binary's spectrum (the Roman numerals show how the star positions correspond to spectral lines)

which the radial velocity curves of the components cross is known as gamma-velocity. It is a projection of the velocity of the binary's centre of mass on the line of sight.

Let us see how much information we can get about a binary star's parameters if we know the radial velocity curve. First, we can determine the absolute dimensions of a binary's orbit from its orbital velocity and period. The wavelength of the light quanta emitted by atoms is the ruler we used to measure the dimensions of a binary. Knowing the semimajor axis and the period, we can use Kepler's third law (formula (2)) to calculate the sum of the masses of the binary star. Is it possible to obtain the individual masses of the stars? Yes, it is. Remember that the ratio of the stars' orbital velocities is equal to the inverse ratio of their masses. It follows that we can use the ratio of the amplitudes of the radial velocity curves to find the ratio of the star masses.

Thus the radial velocity curves and light curves enable us to find both the size of the binary's orbit and the sizes and masses of the individual stars. However, this is possible if the lines of the both stars can be seen in the spectrum and if a binary system is visible from the edge. Otherwise, additional (indirect) information is necessary to estimate the parameters of the stars which make up a binary.

Often we only see the lines of a binary's brighter star in the spectrum. We, therefore, have only one radial velocity curve, i.e. that of the brighter star. One curve is not enough if you are after the mass of the stars, but we make the best of it.

To see what we can learn from a single radial velocity curve, let us first solve a very simple system of four equations. We assume that the stars' orbits in the binary are circular. The sum of the radii of the stars' orbits is obviously equal to the semi-major axis of the binary. This gives us the first equation:

$$r_1 + r_2 = a.$$

The second equation arises from a condition for the distance from the binary's centre of mass to each of the stars:

$$M_1 r_1 = M_2 r_2.$$

Kepler's third law (2) is our third equation:

$$\frac{a^3}{P^2} = \frac{G}{4\pi^2}(M_1 + M_2).$$

The radial velocity curve of star *1* yields a sinusoid's swing (amplitude). We divide it by two and label it K_1. This value is called the semiamplitude. Let us consider its physical meaning. According to the Doppler effect, the shift of a wavelength is proportional to the projection of the star's velocity on the line of sight (a radial velocity), therefore it is clear that K_1 is a projection of the orbital velocity of star *1* on the line of sight. In a uniform circular motion, the orbital velocity is equal to the circumference of the circle divided by the period. Hence,

$$K_1 = \frac{2\pi a}{P} \sin i.$$

This is our fourth equation. By substituting one equation into another and by eliminating r_1 r_2, and a, we get one equation in five variables, namely, the masses of the stars, the inclination of the binary's orbit, its orbital period, and the semiamplitude of the radial velocity curve. Now we simplify the equation so that we have known or directly measurable values on its right-hand side. The rest of the terms called a mass function remain on the left-hand side:

$$f_1(M)=\frac{M_2^3\sin^3 i}{(M_1+M_2)^2}=\frac{PK_1^3}{2\pi G}. \qquad (6)$$

To be more exact, $f_1\ (M)$ is a mass function as determined from the lines of the first star. From symmetry, it is easy to see that should we change index 1 for index 2, we would get the same combination, with M_2 replaced by M_1. This would be a mass function as obtained from the spectral lines of star *2*. Note that the mass function in (6) is measured in the units of mass. Usually it is measured in terms of the mass of the Sun. To plunge deeper into "physics", let us study how the mass function depends on the semiamplitude of a radial velocity curve. Assume that the binary's period is constant while the semiamplitude K_1 increases. Star *1* will thus be moving faster. It moves in the gravitational field of star *2* and its mass must grow. Hence the numerator of formula (6) contains the second star's mass raised to the third power. Of course, in reality the semiamplitude K_1 is a constant. Our thought experiment is a search of different binaries with the same orbital period and angle of inclination. It shows that the mass function contains some, though indirect, information concerning the mass of star *2*.

Note that the mass function is determined spectroscopically, but it does not allow us to find the separate masses of the stars or the angle i. We need additional information, say, from the light curve. Then why is the mass function so important?

The mass function has a valuable property. If we divide $f_1(M)$ by the mass of the second star:

$$f_1(M)/M_2 = \left(\frac{M_2}{M_1+M_2}\right)^2 \sin^3 i,$$

we see that the right-hand side is smaller than or equal to one, which means that

$$M_2 \geqslant f_1(M).$$

This inequality is of great practical value. Suppose you are an astronomer, and one starry night you obtain a spectrum of a mysterious star. In fact, at first you see nothing mysterious. You photograph the spectrum, have a good sleep, develop the plate, and study it thoroughly. You have obtained an ordinary spectrum of a single star. However, you do not give up. On the next night (thank God, it is as starry) you make another photograph of the spectrum repeating your previous procedure. Now you have two spectra of the same star. You start comparing them and discover that some of the lines in the second spectrum have definitely shifted with respect to the lines in the first spectrum. It becomes clear that you have discovered a binary star. None of the catalogues lists the star as a binary, which you know for sure because any astronomer first looks through the catalogues and the literature for information about the object he or she is about to observe.

So the star is binary. Yet you may ask why the second star's lines are not seen in the spectrum. Clearly, the second star is much fainter and cannot be seen against the background of its brighter companion. This makes the object even more puzzling. You spend another month and obtain a light curve which is pure sinusoidal with a period of 1.2 days and a semiamplitude of $K_1 =$ 400 km/s. Substituting these values into (6) you find the mass function $f_1(m) = 8M_{\odot}$. Now you know that, whatever the inclination of the binary's orbit and whatever the mass of the visible star, M_1, the mass of its invisible companion is more than eight times the mass of the Sun. Sometimes such information is extremely important. In Chap. 7, I hope to convince you of this.

Why Are Stars So Different?

If you use a small telescope to observe the binary star system β Cygni, you will see for yourself how different stars are. It is one of the most astonishing sights an amateur astronomer can ever see. The telescope will reveal a pair of stars, one blue and one orange. Why do they differ in colour? Objects around us are differently coloured, and this is because of their different chemical compositions, properties of their surfaces, etc. Yet we know that colour also varies with temperature. For instance, when heated metal first becomes red hot and then white hot. So we want to know whether the difference in star colours is due to the difference in temperature or chemical composition.

We turn to spectral analysis to answer this question. We use a spectrum of a star to determine chemical elements corresponding to the spectral lines. We find that lines of different chemical elements exist in the spectra of differently coloured stars. For example, the strongest lines in the visible spectrum of the Sun are those of calcium. In blue stars, calcium lines are missing while hydrogen lines dominate. The main lines in white stars are those of helium. This means star colour is due to its chemical composition.

However, this is not exactly so. In fact, the intensity of spectral lines indicating the presence of a particular element in the spectrum of a star depends greatly on the temperature of the star's atmosphere. In yellow stars, like our Sun, the strongest lines of the visible spectrum are those of singly ionized calcium ions (that is calcium atom minus one electron). In blue star spectra, however, no calcium lines can be found because the stars are hotter and calcium is almost totally ionized in their atmospheres, i.e. nearly all its electrons have been torn off. When heated, atoms with weakest binding ionize first, and consequently their lines cannot be observed in the spectra of very blue stars, even though the chemical composition of all stars is about the same. In terms of mass, stars contain 70% hydrogen, 29% helium, the rest being heavier elements.

To describe star colour or temperature, astronomers use spectral classification. The seven classes are designated by the letters

O B A F G K M,

with the classes arranged in descending order of temperature, the hottest stars being of several tens of thousands of kelvins (O and B) and the cooler stars being of several thousands of kelvins (K and M). These classes can be memorized with the help of mnemonic phrases, such as, "*O* *B*e *A* *F*ine *G*irl, *K*iss *M*e!"

Initially, seven letters were thought enough. Later, however, a more detailed classification was required. Now each spectral class is subdivided with the numerals 0 through 9 used to indicate subclasses. So the refined classification is ...B9, A0, A1, A2, ... A9... The spectral class of the Sun is G2. There are millions of such stars in our Galaxy.

Stars range widely in temperature from several tens of thousands of kelvins to several thousands of kelvins. The spectral classification allows us to determine the temperature of a star's surface. However, the stars differ even more markedly in luminosity. Note that a star's luminosity L is defined as the amount of energy it produces per unit time. In fact, luminosity is the rate at which energy in the form of light is radiated. The Sun's luminosity is 4×10^{26} W. There are stars which are a million of times more powerful and thousands of times weaker than the Sun. Hence, there is nothing special about the Sun's luminosity.

Astronomers use absolute magnitudes to describe the luminosity of a star. The latter is the magnitude the star would have if it were located 10 parsecs (32.6 light-years) away. In this case, its apparent magnitude would be absolute. The Sun's absolute magnitude is 4.7. But the stars are at different distances from the Earth, their apparent brightness yields no information about their luminosity or absolute magnitude, so how has it been possible to discover that stars have such a wide range of luminosity?

First, we can use binary star systems, in which both companions are equidistant from us. Therefore, if one is brighter, it is certainly more powerful.

In a binary, only two stars may be compared, while in a star cluster several thousand stars can be compared. The closest star clusters to the Earth are the Pleiades and the Hyades, each consisting of hundreds of stars approximately equidistant from the Earth. This fact gives astronomers a good opportunity to study the differences in luminosities. The first astronomer who used this opportunity was the Dane Ejnar Hertzsprung. At the beginning of the 20th century, he observed the Pleiades and the Hyades and plotted two similar diagrams showing the apparent magnitudes of the stars as a function of their temperature. (In fact, he did not use the temperature, but the directly observed degree of blue in their light.)

A few years later, the American astronomer Henry Russell independently began plotting such diagrams for stars located at known distances. Today these diagrams are called Hertzsprung-Russell diagrams. Hundreds of different sorts of diagrams have been plotted by various astronomers over the last hundred of years, but the Hertzsprung-Russell diagram (Fig. 26) has turned out to be most useful.

Even the first Hertzsprung-Russell (H-R) diagrams showed that the stars are not scattered randomly but instead are grouped along certain lines. The overwhelming majority of stars are grouped along a diagonal line called the main sequence. By the way, that's where our Sun is to be found. The

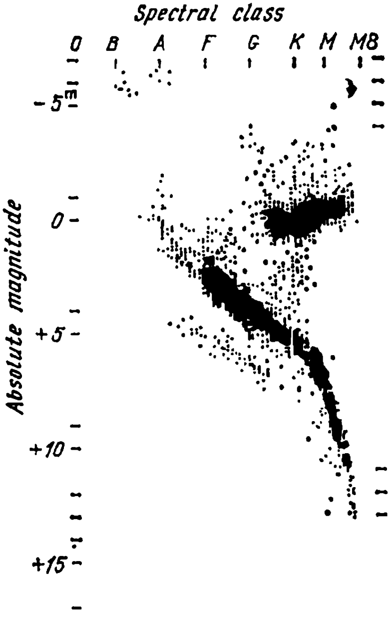


Fig. 26. The Hertzsprung-Russell diagram

most luminous stars form a thick horizontal band. Altogether stars form a slightly distorted Y-shaped curve. That stars "flock together" proves that there is a certain, though complex, dependence between spectral class and luminosity.

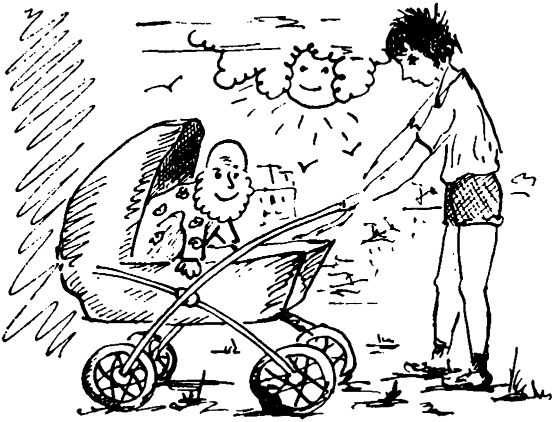
The reason for this mysterious diagram became clear after a breakthrough in our understanding stellar structure and stellar evolution. This theory, which we shall study in detail in the next chapter, explains why most stars are grouped along the main sequence and why the main sequence exists at all. The band is a locus in which stars spend most of the time. The less massive a star is, the colder and dimmer it is. Stars, however, do not stay in the main sequence for ever. Sooner or later, they leave it, to become subgiants, then to become giants, and so on.

The theory of stellar evolution shows that more massive stars spend least time in the main sequence. Stars like the Sun stay on the sequence for billions of years, while blue O-B stars stay for a period hundreds of times shorter. In other words, the more massive a star is, the faster it burns out. The main sequence itself is a sequence of stars with different masses (blue stars are more massive than red ones). The masses of the coldest stars are about a tenth that of the Sun, while the hottest stars are dozens of times more massive than the Sun. So the differences between virtually all the stars in the Galaxy are caused by their different masses.

Finally, a Paradox

The theory of stellar evolution and structure has been brilliantly confirmed by measurements of star masses. We have already seen how the stars in a binary may be "weighed" using radial velocity curves. Many hundreds of measurements have unmistakably shown that the more massive component of a binary is always bluer. That's what we call a triumph of theory.

In the mid-1950s, however, astronomers began to realize that this concord between



theory and observations was not ideal. The disillusioning cracks started from Algol, the most ordinary binary star imaginable. The Soviet astronomers Alla Masevich and

Pavel Parenago were puzzled by the Algol paradox and analyzed its light curve and radial velocity curve. They discovered that the more massive component was on the main sequence, while its less massive companion had left it and turned into a subgiant. Obviously, both stars had been born at the same time. So far there was no explanation of the phenomenon.

The theory seemed so flawless that no one wanted to ruin it because of one little star. It soon became obvious, however, that the Algol paradox was endemic among the binaries. There was only one thing to do, namely, to admit that binaries did not evolve in the same way as single stars, which were described by the theory of stellar structure and evolution.

The only key to the Algol riddle was the assumption that star mass is a variable in a binary star system. Suppose that a less massive star in Algol used to be the more massive one. Now we suppose it left the main sequence, lost some of its mass for some reason, and then became lighter than its neighbour. That would resolve the Algol paradox. But why does a star begin to lose its mass? The explanation was offered by the American astronomer J. Crawford, who suggested a scenario for a binary's evolution with a change in roles.

Changing Roles

The theory of a single star's evolution predicts that a star departing from the main sequence expands. This is why one of the stars in a binary starts losing mass. Suppose we have a binary star composed of two stars on the main sequence. Let star *1* be more massive than star *2*. Initially the stars evolve independently (Fig. 27*a*). Now suppose star *1* is the first to leave the

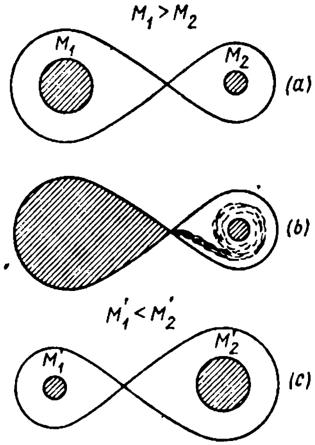


Fig. 27. Changing roles

main sequence and it starts expanding. At a certain moment the first star will fill its Roche lobe. Then the substance of star *1* will flow to star *2* via the inner Lagrangian point (Fig. 27*b*). Suppose the outflow of mass is such that the remainder of star *1* became less massive than star *2*. Thus the flow of mass has reversed the stars' roles. The resultant system has a more massive star on the main sequence and a less massive star which has expanded to the size of a subgiant. Obviously the same occurred in the Algol system.

By the mid-1960s, astronomers had shed more light on this scenario. At the time, nobody realized that the scenario contained a "delayed-action mine". It turned out that the change in roles accounts for the existence in the Universe of some very unusual objects. The discovery and investigation of these objects in the 1970s gave birth to X-ray astronomy, a brand new science.

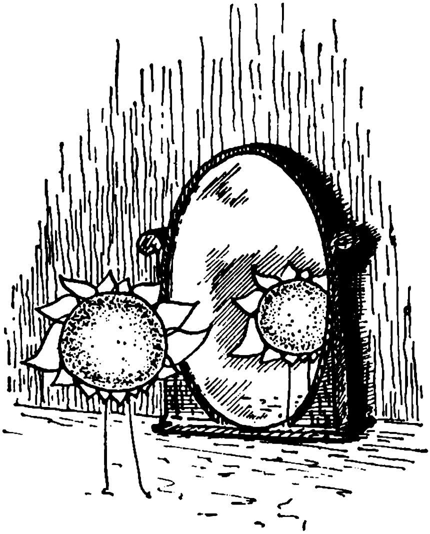
Binary stars whose evolution is accompanied by an exchange of mass are called close systems. The evolution of close binaries is still not completely understood, with the final stages in the evolution of binaries being especially vague. The whole situation is very interesting. The older a binary is, the less we know about it. The reason for this is that at later stages exotic objects appear that only recently have become available to observations.

I would like to invite you for a time journey from the birth to the death of a binary star. I shall try to explain what is happening if I can.

Chapter 3

Living Apart Together

We shall start our time journey through the stages of a binary's evolution from



Living apart together

the very beginning. At this point, the stars are much smaller than the distance between them. This means that they are deep in their corresponding Roche lobes and do not affect each other. Both stars evolve as if they have no companions. Binary or not, they live the life of a single star.

In 40 Minutes Only

Even though the Sun is vast (its radius is 700000 km), it only creates a gravitational potential at its surface 3600 times that on the Earth's surface. Do you remember formula (1) for the potential of a point body? It remains valid outside a spherical body of random size. The potential is measured in the units of energy per unit mass, which are the dimensions for the velocity squared. The potential (its absolute value) is, in fact, equal to the kinetic energy of a test particle having a zero total energy. Zero energy particles are those which fall freely from infinity. Freely falling onto the Earth's surface, a body would have a speed of 11 km/s, while on the surface of the Sun it would have 617 km/s. The square of the ratio between these two speeds is about 3600. The Sun has a higher value because of its mass (the Sun's mass is $M_{\odot} = 2 \times 10^{30}$ kg and the Earth's mass is $M_{\oplus} = 6 \times 10^{24}$ kg).

Gravity seeks to compress the Sun, but the Sun does not shrink because the inward pressure due to gravity is strictly balanced by the outward gas pressure forces of the Sun. If at some moment the gas pressure disappeared, it would take the Sun only 40 min to collapse to a dot. Yet the Sun has been shining for billions of years without any significant change in size. The time it would take the Sun or other star to collapse is called dynamic time. It is approximately equal to the ratio between the star's radius and the escape velocity on its surface:

$$t_D \simeq R_\odot / v_{II}. \tag{7}$$

The collapse time (i.e. 40 min for the Sun) may be calculated very accurately. Assume that the pressure inside the Sun has disappeared and the Sun begins to "fall into itself". To see how long this will take, recall that the gravity outside a sphere is the same as the field of a point with the same mass at the sphere's centre. So, we need to calculate how long it takes a test particle to fall to a point whose mass equals that of the Sun from a distance equal to the Sun's radius. The motion of such a particle is called free motion in a potential well, which can be described by Kepler's laws. It (motion along a straight line) can be represented as moving along an ellipse with an eccentricity of one and a semimajor axis of half the Sun's radius.

It is obvious that the time we desire is half the period of revolution along a collapsed ellipse, the period being determined by Kepler's third law (formula (2)). Assuming that $M_1 = M_\odot$ and $M_2 = 0$, $a = R_\odot/2$, we obtain

$$t_D = \frac{P}{2} = \frac{\pi}{2}\sqrt{\frac{R_\odot}{2GM_\odot}} \simeq 40 \text{ min.}$$

You see that the estimate (7) does not differ much from the accurate result. The fineness with which gravity and pressure are balanced in the Sun can be seen from the ratio of the dynamic time to the age of the Sun, i.e. approximately 10^{-14}. You might get the impression that the Sun is fragile. Suppose the pressure and the gravity were several percent off-balance. Clearly, the Sun would collapse in a few hours. This, however, does not happen. Now let us see why.

The balance in the Sun and other stars is stable. We know that a stable equilibrium always means that the system's energy is at a minimum. The star's energy is composed of its potential gravitational energy and the kinetic energy of its particles, i.e. ions and electrons. All the kinetic energy in stars is concentrated in the chaotic motion of particles. (The rotation of the Sun adds very little to the kinetic energy of its particles; this is why the Sun is round.) The particles' chaotic motion is thermal; therefore, the Sun's kinetic energy is its thermal energy. The Sun's total energy E is the sum of the thermal energy K

and the potential energy U:

$$E = K + U.$$

Now we shall see how stable a star is by compressing it. Figure 28 shows how the star's total energy varies with radius. On

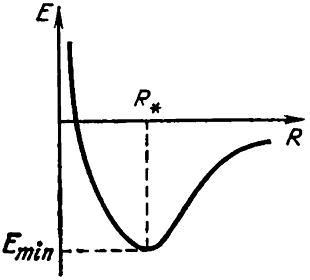


Fig. 28. A change in the star's energy during compression and expansion

being compressed, the star's thermal energy rises faster than its gravitational energy falls. True, the star's total thermal energy K is proportional to the star's mass times its temperature: $K \propto \mathcal{R} MT$, where $\mathcal{R}$ is the gas constant. We shall assume that the star's compression is so fast that it does not have time to give off heat. Such compression is called adiabatic. When adiabatically compressed, the temperature of a monatomic gas depends on the volume as $T \propto V^{-2/3}$. But the star's volume is $V \propto R^3$;

therefore, $T \propto R^{-2}$. The thermal energy grows during the star's compression as $1/R^2$. In contrast to this, the star's gravitational energy is proportional to the potential, i.e. it grows as $1/R$ (see formula (1)). The graph in Fig. 28 is the sum of two hyperbolas, a positive quadratic one and a negative first-order one. The energy minimum ($E_{\min}$) corresponds to the star's equilibrium radius R_*.

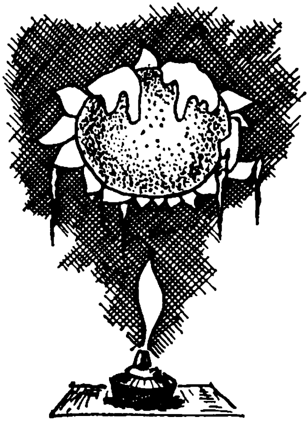
I have already mentioned that during a star's compression its thermal energy rises faster than its gravitational energy does. Therefore, the pressure forces grow faster too. In other words, the star tends to expand. Like a spring, the star will vary in size about some equilibrium, and the period of the variations will be of the order of its dynamic time. For the majority of stars, this time varies between dozens of minutes and several hours.

Getting Hot by Cooling

In equilibrium, the star's energy, like the total energy of a binary, is negative. This is a common property of any gravitationally related system. The thermal energy K in equilibrium is always of the same order as the gravitational energy (but with the opposite sign). This accounts for the astonishing property of a star, namely, its negative heat capacity. If you heat any normal object, in other words, if you increase its energy, it will get hotter because it has a positive heat capacity. It is the other way around with a star. An increase in the star's total energy (heating it up) lowers its thermal energy, i.e. its average temperature. Indeed, if you increase the star's energy (heat it up), it must expand and attain a new state of equilibrium. This, however, will be accompanied by a fall in the absolute value of the gravitational energy (the radius has grown) and a fall in the thermal energy. The star will become cooler! The reason is that an increase in energy causes the star to expand and do work to overcome gravity. That's what accounts for the cooling.

This does not contradict the laws of thermodynamics. It might seem unusual to us because on Earth we are used to dealing with objects whose equilibrium is supported by short-range forces. As a rule, these are the forces of molecular attraction (in fact, they are ordinary electrostatic forces acting between charged parts of molecules even though, on average, the system is neutral). Considering some small segment of a body, we ignore its interaction with other parts not touching it. We can do this because both negative and positive electric charges exist in nature and they screen each other. In contrast, gravitational charges or masses always have the same sign since there is no antigravity.

That is why gravity is long-range. Any part of a star "feels" both the attraction of its immediate neighbour and that of all the other components of the star. Thus,



A star's negative heat capacity

a common gravitational field creates a pool of negative energy. When a star expands, this reserve turns into an insatiable consumer. When the star becomes colder and smaller, it is a heater. Look at the stars that are shining. Now you know that this means they must shrink to lose their energy.

As Little As 30 Million Years

The total thermal energy in a star is approximately equal to its gravitational energy taken with the opposite sign, i.e. it is of the order of GM^2/R. The thermal energy of the Sun is 4×10^{41} J. Every second the Sun loses 4×10^{26} J of energy. This means the Sun should run out of energy in 30 million years. The time it takes a star to lose its energy is called its thermal time

$$t_T \simeq K/L. \qquad (8)$$

The Sun and the Earth, however, have remained nearly the same for several billions of years. Consequently, the Sun must have an inner source of energy to make up for what is lost. We have already discussed the gigantic pool of gravitational energy in the star, but it is not inexhaustible. The Sun must shrink to half its size every 30 million years. Some other source of energy must exist.

The source was discovered by Sir Arthur Eddington, an English astronomer and the father of the modern theory of stellar structure. He worked at Cambridge University, as Newton had done some 200 years earlier. Eddington suggested that nuclear energy is produced inside the Sun. This idea is much older than the H-bomb.

Let us look at where nuclear energy comes from. Atomic nuclei are a mixture of neutrons and protons (nucleons). The total energy of a nucleus is made up of the potential energy of the nuclear interaction, the electrostatic repulsion of protons, and the kinetic energy of all the particles. Figure 29 shows a graph of the energy per one

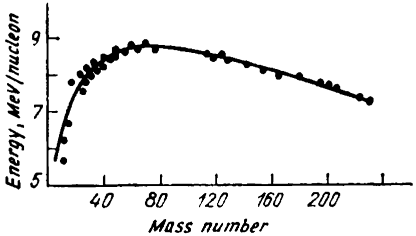


Fig. 29. The average binding energy per one nucleon in the nuclei of different chemical elements

nucleon against the mass number. The average energy per one nucleon in a nucleus, if taken with the opposite sign, shows how closely the particles in a nucleus are associated (or, in other words, how deep the potential well in which they found themselves is). The graph indicates that the strongest bonds exist in the elements near iron. The lighter elements only have a few nucleons in a nucleus and the nuclear interaction energy is proportional to the square of the number of particles. (Each particle interacts with all the rest! By the way, this is why gravitational energy is proportional to the square of mass.)

The amount of energy per particle grows with increasing the number of nucleons. This is true as long as the nuclei are light. Nuclear forces are extremely short-range. They act at a distance of 10^{-13} cm, but, as the distance grows, fall to zero. For this reason in nuclei with many particles nucleons only interact with their immediate neighbours. By contrast, electrostatic repulsion, whose energy is positive and which is long-range grows continuously and is directly proportional to the square of the number of nucleons (protons and neutrons are present in nuclei in approximately equal numbers). Therefore, the nuclei of elements heavier than iron have smaller binding energies. The graph shows that it is energetically more favourable for lighter elements to fuse into heavier ones and for heavy elements to break into lighter ones. (The fission of heavy elements is used in nuclear power plants.)

The fusion of light elements into heavier ones is accompanied by a terrific release of energy. For instance, four nuclei of hydrogen (protons) have a mass of 6.69×10^{-27} kg, while a nucleus of helium weighs 6.65×10^{-27} kg. This mass defect is explained in relativity theory and, according to Einstein's mass-energy relation, a body's total energy is related to its mass thus

$$E = Mc^2. \tag{9}$$

The binding energy per one nucleon in helium is greater, so its potential well is deeper and its total energy is smaller. If we could convert 1 kg of hydrogen into helium, the liberated energy would amount to 6×10^{14} J. This is about 1% of the total energy of the fuel consumed. Here is an energy reserve.

When Eddington suggested that a star's energy is nuclear in nature, his hypothesis was given a "death blow".

But for Quantum Mechanics

His critics, staying within the framework of existing laws, "proved" that fusion is impossible at the centre of the Sun. Figure 30 gives a graph of how the interaction

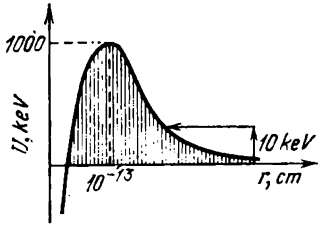
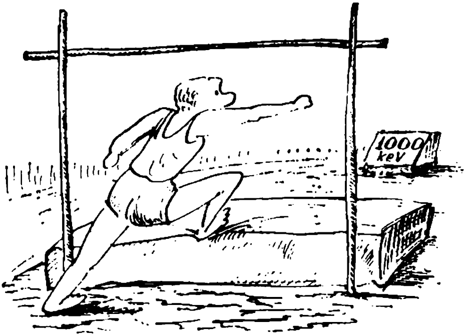


Fig. 30. Interaction energy between two protons against the distance between them

energy of two protons is related to the distance between them. At greater distances, the interaction is governed by the electrostatic repulsion of two positively charged particles. The interaction energy is positive and, as the particles get closer together, grows as $1/R$. At a maximum, this energy is approximately 1000 keV Then, at about 10^{-13} cm, the nuclear interaction creates an area with negative ener-



Quantum tunneling effect

gies, which corresponds to the bound state. To get into the negative energy area, however, a barrier of 1000 keV must be overcome.

We can estimate the temperature at the centre of the Sun by assuming that the thermal energy and the gravitational energy are about the same ($\mathcal{R}MT \simeq GM^2/R$), and the resultant figure is ten million kelvins. The average energy of protons at such a temperature is about 1 keV, which is a thousand times too small for helium fusion. The critics maintained that it was too cold at the centre of the Sun for fusion. This did not embarrass Sir Arthur Eddington, who stubbornly suggested they should look for a hotter spot. What was once believed to be obstinacy is now called intuition.

The advent of quantum mechanics ended the argument. Developed in 1926, quantum mechanics was soon applied to astronomy and revealed the astonishing properties of the microcosm. One such property is tunneling, i.e. particles' penetration of a potential barrier. Elementary particles appear to be able to penetrate a barrier even if their own energy is smaller than that of the barrier. Suppose a high jumper were to run under the bar, the judge would hardly be likely to say the jump was fair. The laws of nature are not so "strict".

Clearly, the most visible quantum effect is the shining of the stars. What would happen if there were no quantum mechanics?

Nuclear Evolution

The conversion of hydrogen into helium is irreversible, and the reserves of hydrogen in a star are limited. Moreover, fusion reactions require high temperatures and densities to proceed. At the centre of the Sun, the density is 100 g/cm^3. Thus only the hydrogen in the star's central core, some 10% of the star's total mass, can go to fuel it. Now let us see how long it will take the Sun to run out of its nuclear fuel.

The Sun's total energy is $M_{\odot}c^2 = 10^{47}$ J, nuclear energy E_{nuc} is about 1%, i.e. about 10^{45} J. Given that not all the fuel may burn, we get 10^{44} J. By dividing this quantity by the Sun's luminosity $L = 4 \times 10^{26}$ J/s, we conclude that it will take ten billion years for the Sun to burn out. This is consistent with geological data concerning the Earth's age. On the other hand, it means that stars are not eternal, they evolve. Their nuclear evolution is determined by the gradual exhaustion of the light elements. This period is called the nuclear time and it is given by the formula

$$t_{\text{nuc}} \simeq \frac{E_{\text{nuc}}}{L} \simeq 10^{10}\left(\frac{M}{M_{\odot}}\right)^{-2} \text{ years.} \qquad (10)$$

The nuclear time versus the mass of a star may be calculated if we remember that the star's nuclear energy is $E_{\text{nuc}} \propto Mc^2$, and that luminosity behaves approximately like $L \propto M^3$. I would like to emphasize here that the right-hand side of (10) is only a rough approximation. The result is that the larger a star, the faster it burns itself out.

Now let us return for a while to the H-R diagram. Most stars are grouped along the main sequence. These are stars at whose centres hydrogen is burning. I say hydrogen and I mean it. The heavier elements require higher temperatures to start fusing (their potential barrier is higher) and this is accompanied by the departure of the star from the main sequence.

Let us compare the star's nuclear time and its thermal time (see formula (8)). An approximate relation between the thermal time and the star mass is

$$t_T \simeq 3 \times 10^7 \left(\frac{M}{M_\odot}\right)^2 \text{ years.} \tag{11}$$

The dynamic, thermal, and nuclear times determine the star's evolution. Because the dynamic time is much less than thermal and nuclear times, the star always has time to attain hydrostatic equilibrium. Furthermore, because the thermal time is less than the nuclear one, it also has time to attain thermal equilibrium. In other words, there is always an equilibrium between the amount of energy emitted at the centre per unit time and the amount of energy radiated by the star's surface (a star's luminosity). Every 30 million years the store of thermal energy in the Sun is renewed. But the energy in the Sun is transferred by radiation, in other words, it is carried by photons. A photon that is born in a fusion reaction at the centre appears on the surface after about 30 million years.* If the ther-

* Although it will be quite another photon (see below).

monuclear energy supply were stopped today, the Sun would continue to shine for many more millions of years.

Burning hydrogen not only produces photons it also yields neutrinos. The latter leave the Sun at the velocity of light, that is, it takes 700000 km : 300000 km/s = 2.3 s (the Sun's radius in light seconds).

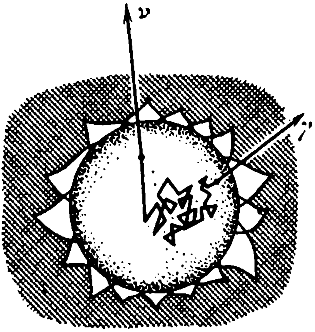


Fig. 31. The trajectories of a photon (γ) and a neutrino (ν) emitted from the centre of the Sun

How come that it takes a photon, which also travels at the velocity of light, as much as 30 million years to cover the same distance? Clearly, because the photon is repeatedly absorbed and reemitted. Its trajectory is thus so complex that it has to travel 30 million light-years, i.e. the distance to distant galaxies (Fig. 31). Over such a long period the radiation attains thermal equilibrium with the matter in which it is moving. Therefore, a star's spectrum is close to the spectrum of a blackbody.

The theory of the structure of main-sequence stars worked out by Eddington in

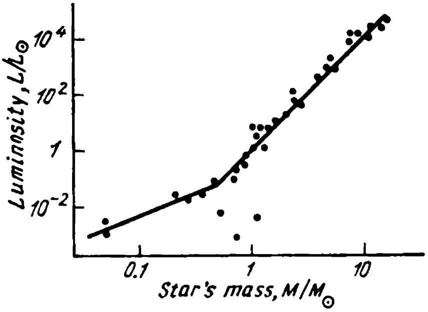
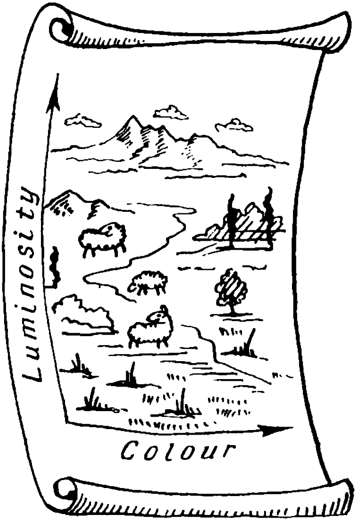


Fig. 32. The observation of binaries made it possible to plot the mass-luminosity relation for main-sequence stars

the early 1930s fully explained their observed properties. The H-R diagram, however, features luminosity-spectrum dependence which, in turn, is a function of star masses. This means that a final verification of the theory demanded that the stars be weighed. That's when binary stars were handy. Photometric and spectral observations of binaries made it possible to determine the masses of many hundreds of stars and their relationships with luminosity (Fig. 32). This relationship revealed consistency between observation and theory. However, the theory failed to explain why some stars in the H-R diagram do not lie on the main sequence.

Fleeing the Main Sequence

The line along which a star moves in the H-R diagram is called an evolutionary



Oh, flocks of stars! Like sheep you roam.
Who is your shepherd? Where is your home?

track. The first astronomer to introduce nuclear reactions into the calculations of stellar structure was an American named Martin Schwarzschild. His calculations explain why the stellar groups wander to and fro.

Initially, a star starts crawling up the main sequence. At this stage, the star's luminosity and its temperature vary with gradual changes in the chemical composition of its core. Hydrogen turns into helium until it burns out completely. First it happens in the core where the density and temperature are at a maximum. Thus a helium core is formed. Although the temperature in the core is not high enough to sustain the burning of helium, hydrogen keeps on burning in a shell surrounding the core. Such a process is called burning in a shell source. The helium core thus finds itself inside the source of energy; the temperature in the core becomes constant, and such a core is said to be isothermal. As the shell source is formed, the flow of energy to the surface of the star increases. The envelope around the shell source becomes turbulent like water boiling in a kettle.

The analogy with a kettle is more than superficial. At a certain moment, the water in a kettle starts bubbling because the water's heat conductivity is too small to transfer the heat supplied from the bottom. Heat is transferred in fluids by a mechanism called convection. The warmer and less dense water at the bottom rises in accordance with Archimedes' principle. The instability of a denser fluid being above a lighter fluid is called Rayleigh-Taylor instability.

The formation of the shell source leads to the formation of a convective envelope.

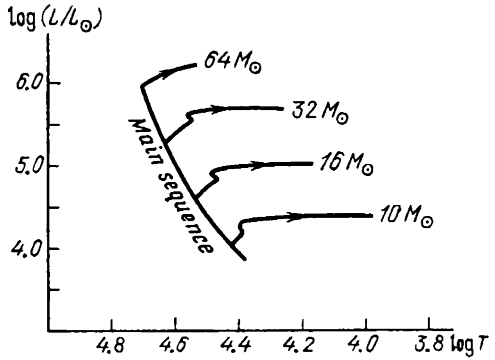


Fig. 33. Stars of different masses leaving the main sequence

The star expands. In the H-R diagram, this is manifested as a departure from the main sequence towards giants and supergiants (Fig. 33).

Have you ever seen peat burning in a peat bog? You don't actually see any fire, only smoke. The peat burns in a small ring-shaped segment. Gradually the segment grows wider and the yellow patch of faded grass inside the circle expands.

The same happens to a star. As the hydrogen begins to fuse, the mass of the helium core increases (Fig. 34). The core becomes too large and the expansion is halted and then reversed. What happens next

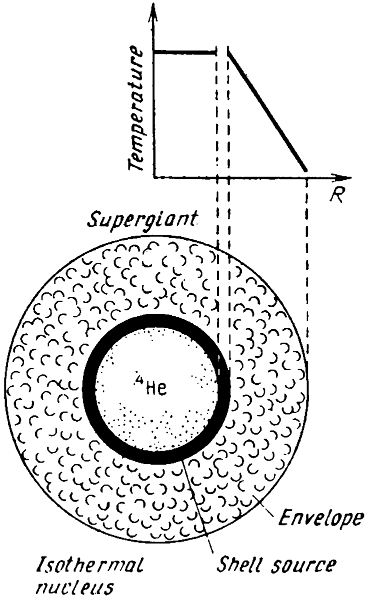


Fig. 34. The structure of a supergiant

depends on the mass of the star. In a very massive star, the temperature in the helium core rises until it is high enough for the helium to turn into carbon. This occurs when three helium nuclei (α-particles) fuse, therefore, it is sometimes called the 3α process.

A star may have two or more shells. In stars with masses exceeding $10M_{\odot}$, the nuclear fusion even involves elements belonging to the group of iron. Such a star is a blue supergiant. Its radius increases hundredfold and in some cases becomes thousands of times as great as that of the Sun. If you were to place such a star in the Solar System instead of the Sun, the Earth would be deep inside it (the distance between the Sun and the Earth is equal to 214 radii of the Sun). What is the final outcome of the stellar evolution?

White Dwarfs

Eddington's theory elegantly explained the positions of the stars in the H-R diagram. Given the mass and chemical composition of astar, all the observed parameters including luminosity, radius, surface temperature, etc. could be obtained. However, one starlet, namely, 40 Eridani B, seemed to spoil the whole picture. It was located in the H-R diagram below and to the left of the main-sequence stars. Even though it has a high temperature, it was glowing too feebly and was thus too small. Eddington's theory could not explain this.

The puzzle was solved by the English physicist Ralph Fowler in 1926. Those were years of great discoveries in physics. Between 1925 and 1927, the German physicists Werner Heisenberg and Erwin Schrödinger developed quantum mechanics. In 1927, Heisenberg enunciated the uncertainty principle, which stated that it is impossible to know both the coordinates and velocity of an elementary particle at the same time. At that time, Wolfgang Pauli proposed his famous exclusion principle, which stated that no two electrons in an atom may be in the same quantum state. Enrico Fermi and Paul Dirac studied the fundamental properties of matter using quantum-mechanical principles. These discoveries showed that under certain conditions matter starts behaving in an unusual manner.

Eddington's theory starts from the assumption that a star consists of an ideal gas, i.e. matter satisfying the equation

$$P = \rho \frac{\mathcal{R} T}{\mu}, \tag{12}$$

where P and ρ are the pressure and density of the matter respectively, and μ is its relative molecular mass. The relative molecular mass is the average mass of one particle expressed in masses of an atom of hydrogen. This definition is also true for plasma, which has no molecules whatever. Accurate measurements show that the relative molecular mass of fully ionized hydrogen plasma is 0.5. The mass of a pair of particles (an electron and a proton) is almost as much as that of a proton (the electron has a mass 1800 times less than that of a proton).

According to the classical definition, an ideal gas is one in which particles are much smaller than their mean free path. Have you ever asked yourself why the density of objects around us is close to 1 g/cm^3? The density of water, for example, is equal to 1 g/cm^3. Let us try to answer this question.

If we cool bodies around us, their densities will not be significantly changed. It can only mean one thing: these bodies are already so cold that the particles they are made of touch and further cooling will cause no further contraction. The world we inhabit is cold! The density of bodies we come across in everyday life is the density of the atoms they are made of. A hydrogen atom has a mass of 10^{-24} g and a diameter 10^{-8} cm. Dividing the mass by the cube of the dimension, we get 1 g/cm^3. This means that the atoms and molecules in solids and liquids are packed so closely together that they are far from being ideal gases. Now let us turn to the density of the Sun. If we divide the mass of the Sun (2×10^{33} g) by its volume $(4/3)\,\pi\,(7 \times 10^{10})^3$ cm^3, we get 1.4 g/cm^3. That is, the Sun is denser than water and yet it is very much an ideal gas. Why?

Let us recollect the definition of an ideal gas: particles' mean free path is much greater than their dimensions. The mean free path is the average time between successive collisions multiplied by the speed of a particle. As the density grows, the time between the collisions decreases and so the mean free path becomes shorter. But if the density increase is accompanied by an increase in the speed of particles, the mean free path may even become longer. We know that the speed is proportional to temperature and this is the key to the puzzle! The Sun's matter is so hot that even though it has a density exceeding 1 g/cm^3, it remains an ideal gas (or, to be more exact, a plasma). Clearly, if the contraction of the Sun is not accompanied by a significant rise in its temperature, its matter will sooner or later stop being an ideal gas.

If we admit that the Sun could be compressed, its matter will cease to be ideal sooner for quite another reason. It is worthy of note that as early as the end of the 19th century the famous Russian inventor and rocket expert Konstantin Tsiolkovsky suggested that if the Sun contracted, its matter might be converted into another state that cannot be described by the ideal gas equation. Considering radiation-induced star contraction, Tsiolkovsky admitted that at some density further contraction would not be possible due to deviations from the ideal gas condition. Surely, he could not know that the reason lay in the laws of quantum mechanics. It was Fowler who first noted that if a star was contracted 10-100 times, the electrons would be pushed apart due to Pauli's exclusion principle. At densities of 10^5-10^8 g/cm^3, protons and ions would be so close together that their atomic levels would unite. Electrons also unite to form a special degenerate gas. When Fowler used an equation of state for a degenerate electron gas, he discovered that such stars would be about 5000-10000 km in diameter, i.e. about the size of a planet. This explained the contradiction of 40 Eridani B and other stars of this type. Such stars are called white dwarfs.

If a star's mass is less than $3M_{\odot}$, a helium core grows at its centre which contracts to become a white dwarf. The contraction generates gravitational energy which heats up the envelope; then the latter cools, i.e. it expands and leaves the star in the form of a ring-shaped nebula. This may be the way planetary nebulae are born (Fig. 35). As a rule, at the centre of such a nebula, there is star which is as hot as it is compact; it is not unlikely that the star is a helium core being cooled.

In more massive stars, the temperature at the centre is high enough to initiate the fusion of heavier elements. If the star's nass is less than about $8M_\odot$ a core of arbon and oxygen grows in its interior. 'he contraction of such a core, provided its nass is close to the Chandrasekhar limit,

'ig. 35. A planetary nebula in the constellation Aquarius

s not as harmless as it is in the case of helium core. The carbon begins to fuse it the star's centre. As a result, the burning spreads slowly throughout the star.

This process is known in explosive chemistry and is called deflagration. At a certain moment, the hydrostatic equilibrium is disturbed and the star begins pulsating with a growing amplitude. This pulsation may result in the explosion and complete disintegration of the white dwarf. The energy thus produced is comparable to that of a supernova explosion. The star ejects heavy elements into interstellar space where new stars or planetary systems form and which will probably be able to support life.

Finally, in stars with masses of (8-10) $M_{\odot}$, the carbon is completely used up and a core consisting of a whole set of elements including oxygen, neon, and magnesium is formed. Later this core cools and becomes a white dwarf. The extra material disperses "quietly" in the form of a planetary nebula.

Neutron Stars

A degenerate gas possesses the remarkable property that its pressure is independent of temperature and varies only with the density as $P \propto \rho^{5/3}$. However cold a white dwarf may be, it will never contract. The white dwarf's equation of state reveals an unusual relationship between its radius and mass.

The pressure of gravitational forces is $P_{gr} \simeq (GM^2/R)/4\pi R^2 \simeq M^2/R^4$, while the pressure of the gas is $P \propto \rho^{5/3} \propto (M/R^3)^{5/3} \propto M^{5/3}/R^5$. At equilibrium, both pressures must be equal; therefore, $R \propto M^{-1/3}$. It follows that increasing the mass of a dwarf decreases its radius and increases its density. A rise in density, however, is accompanied by a rise in the energy of the electrons. As is known, electrons in an atom seek to occupy the lowest levels and the same happens in an electron gas. But in a degenerate electron gas all the lowest levels are occupied, and thus are "closed" to the electron according to the Pauli exclusion principle. As the mass of a white dwarf and, hence, its density increase, the electrons will be "packed" more and more closely. Since there is no room at the bottom, the electrons will have to move to upper "shelves" where the energy is higher. Little by little, the electron energies become comparable with their rest energy m_ec^2. Thus the electron gas turns into a relativistic gas which is much more compressible. Here the pressure is $P \propto \rho^{4/3}$, i.e. $P \propto (M/R^3)^{4/3} \propto M^{4/3}/R^4$. During compression, gas pressure grows in the same manner as the pressure of gravitational forces. This means that a white dwarf may only be in equilibrium at a certain value of mass; this critical value is approximately $1.5M_{\odot}$ and is called the Chandrasekhar limit. It was obtained by a twenty-year old Indian physicist Chandrasekhar in 1931. For his theoretical study of white dwarfs he was awarded the 1983 Nobel Prize in physics.

If a star's mass exceeds the Chandrasekhar limit, the electron gas pressure can no longer balance gravity and contraction will continue. Independently of Chandrasekhar, the limit was obtained by the Soviet physicists Yakov Frenkel and Lev Landau. Landau wrote that a star with a mass above the critical limit will continue to contract until the nuclei come into contact making up a single nucleus of enormous size. Landau wrote this article a year before the neutron was discovered. At the time, physicists did not know that protons and electrons could fuse to form neutrons. Another year passed and American astronomers Walter Baade and Fritz Zwicky hypothesized that a supernova explosion is the result of an ordinary star's collapse into a star consisting only of neutrons. Such stars were called neutron stars. The density of these stars is close to nuclear density, i.e. 10^{13}-10^{15} g/cm^3. It means the size of a neutron star with closely packed neutrons is $(10^{15}/1)^{1/3}$ times smaller than the Sun whose average density is close to unity. It follows that the neutron star's radius is about 10 km even though its mass exceeds that of the Sun.

Neutron stars are the end result of the

evolution of stars whose initial masses are more than $10M_{\odot}$. It must be massive in order to be able to sustain the fusion of the heavier elements after the lighter elements have been exhausted. In such stars everything up to iron is burnt out. Further fusion produces no more energy and, instead, starts to consume it. Therefore, once the contraction of an iron core has begun, it cannot be stopped.

The gravitational energy produced feeds the fusion of the heavier elements, the contraction becomes disastrous, and collapse takes place. During the collapse, the amount of energy liberated is so great that the whole envelope is ejected with a velocity of several tens of thousands of kilometres per second, and this is what we observe when we see a supernova explosion. Baade and Zwicky's hypothesis was convincingly confirmed in 1968 when the Crab radio pulsar was discovered in what might be the remnants of a supernova explosion.

The radio pulsar's signals come to us as a sequence of very regular narrow pulses. The pulsar's light curve looks like an old comb with widely spaced teeth (Fig. 36). The teeth (pulses) may disappear but when they emerge they do so in accurately predictable places (moments). The equidistant teeth of a comb are made by a machine, but why are a pulsar's signals so very regular? The reason is that they are emitted by a rotating neutron star. Indeed such a star is the only body that can rotate with a period of 0.033 s. Any other star would be torn into pieces by centrifugal forces.

The American astrophysicist Thomas Gold first realized that radio pulsars are

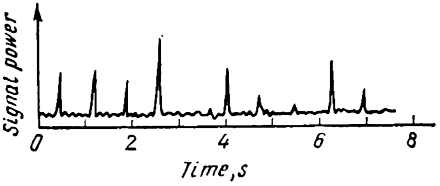


Fig. 36. The recorded radio signal from the pulsar PSR 0329 + 54, which was one of the first to be discovered

neutron stars whose energy comes from their rotation and whose magnetic field is a drive belt which transfers the energy from the star. The magnetic field of a neutron star, like that of the Earth, is dipolar. In other words, there is a line passing through the magnetic poles. Fluxes of relativistic particles and radiation are ejected along this line (Fig. 37). The pulsar "illuminates" space like a rotating searchlight. Periodically the beam strikes the Earth and we have an opportunity to receive it. However, the signals must slow down the rotation rate, and this is exactly what is observed. The pulsar's periods gradually increase (Fig. 38). It is not yet clear, though, why neutron stars

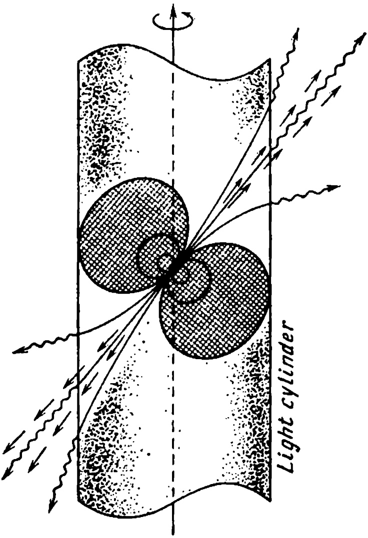


Fig. 37. The magnetosphere of a radio pulsar

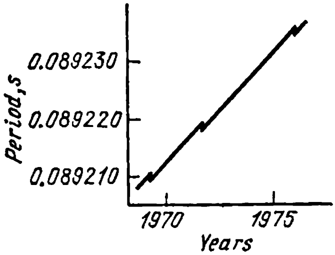


Fig. 38. A change in the period of a radio pulsar in the constellation Vela

rotate so rapidly and possess such strong magnetic fields.

The rapid rotation, a strong magnetic field, and an accompanying nebula are the birthmarks of a neutron star. The only difference between them is that the nebulae disperse after several tens of thousands of years and become invisible, while the rotation and the magnetic fields retain for many millions of years.

The pulsar's unique properties prove that neutron stars are born when ordinary stars collapse. To be more exact, it happens to their iron cores. This core, which grows at the centre of a massive star, may have a mass exceeding the Chandrasekhar limit. Its collapse is accompanied by a terrific outburst of energy produced by gravitational forces. There is enough energy to shake off the star's massive envelope (and thus produce the nebula, that is, the remnants of the supernova), increase the magnetic field, and accelerate the rotation.

It is not yet clear how the envelope is shaken off. As the star's iron core contracts, atomic nuclei are pressed together, the matter's neutronization sets in, and the protons p^+ unite with the electrons e^- to form neutrons n, i.e.

$$p^+ + e^- \rightarrow n + \nu.$$

This reaction also produces neutrinos ν. Neutrinos that take up the energy. The density is so high that even neutrinos with their all-penetrating ability cannot find a direct way out of the star. They are absorbed (like, for example, in reverse reactions) and give off their momentum. A powerful neutrino pressure emerges. Astrophysicists believe that it is this pressure that pushes away the star's envelope. This view is confirmed by the existence of neutron stars.

In some cases, however, the envelope is not shaken off. You may wonder whether it is possible for a massive neutron star to be formed. The answer is no. Massive neutron stars do not exist.

Black Holes

Just as white dwarfs cannot have a mass exceeding the Chandrasekhar limit, neutron stars cannot be infinitely large. This was first discovered by the American physicists R. Oppenheimer and G. Volkoff in 1939. Unfortunately, the accurate value of the Oppenheimer-Volkoff limit is still unknown. because we do not know how matter behaves at densities exceeding nuclear density. This limit is now estimated to be (2-3) $M_{\odot}$. In a more massive star, no pressure can withstand gravity. The star collapses and a black hole appears.

Early in the 19th century the great French scientist Pierre Laplace used Newton's law of universal gravitation to invent what was later called black holes. Simple reasoning brought him to an astonishing conclusion.

If you want to get a freely moving body off the surface of an attracting body you must attain its escape velocity

$$v=\sqrt{2\frac{GM}{R}}.$$

For the Earth, it is 11.2 km/s, for the Sun it is 600 km/s. If we start compressing the body, the escape velocity will grow. At a certain radius, it will reach the velocity of light. This critical radius which is now called the gravitational radius is

$$R_{gr}=\frac{2GM}{c^2}. \tag{13}$$

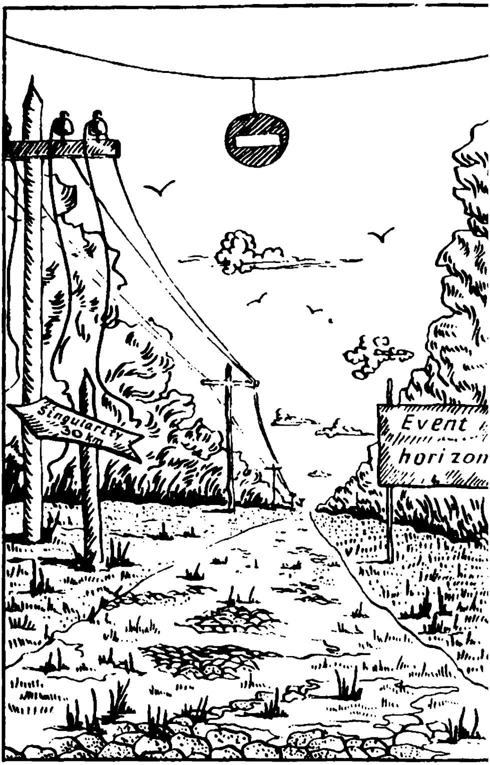
For the Sun, R_{gr} is equal to 3 km. A body with such a radius cannot shine because the light cannot leave its surface.

In fact, our calculations are wrong. If the body's size is of the order of the gravitational radius, Newton's theory can only give an inaccurate picture of the phenomenon. A rigorous solution of the problem of the gravitational field for such a body demands that we solve the equations of general relativity. This was done in 1916 by the German astronomer Karl Schwarzschild, the father of Martin Schwarzschild, who first calculated the nuclear stellar evolution. It is interesting that the rigorous solution contains a quantity having the dimensions of distance and the formula for it coincides with formula (13). That's where the similarity with Newton's theory ends. In Schwarzschild's rigorous solution, something more subtle happens at the gravitational radius than mere equating the velocity of light and the escape velocity.

You do not need to develop escape velocity to leave a body, this requirement is only necessary for a freely moving body. You could leave the Earth at a snail's pace; what you would need is an engine that never stops working. Similarly, you could flee a Laplacian black hole with the help of, say, a ladder.

But, however hard you try, you will never be able to escape from under the gravitational radius. No engine can help you out, because gravity rises to infinity. The road to a black hole is like a one-way "anisotropic" road in the novel *Hard to Be God* by A. and B. Strugatski.

This is not the only paradox of relativity theory. For a distant observer on Earth, the black hole never forms completely. The reason for this is the lack of time. In a strong gravitational field, time itself slows down. If you were to look at a clock on a collapsing star, it will be slower than our (laboratory) clock. As you approach the gravita-



The road to a black hole resembles an "anisot road tional radius, the time dilation grows to infinity. The star will contract to the size of the gravitational radius over an infinitely long period of time. This is why black holes are sometimes called frozen stars.

Things would be different if we were unlucky and found ourselves on the surface of a contracting star. We would reach the gravitational radius in a matter of seconds. Even then nothing terrible would happen (provided we could survive the tidal forces). But as soon as we cross the gravitational radius, we would be hopelessly lost from the rest of our Universe. Our cry for rescue would accompany us in our fall into the black hole. Now it is easy to see why the surface with radius R_{gr} is called the event horizon.

Ancestors and Descendants

Let us make a brief summary. A star's future depends on its initial mass. Less massive stars (lighter than 2-3 masses of the Sun) give birth to helium white dwarfs (Fig. 39); the greater the mass, the heavier the core. (When I say "heavy", I mean both the mass and the mass number of chemical elements.) Stars with masses of $(8\text{-}10)M_{\odot}$ produce white dwarfs composed of carbon, oxygen, etc. The masses of white dwarfs are less than the Chandrasekhar limit (about $1.5M_{\odot}$). It is interesting that in a carbon core

with a mass close to the Chanc
limit the liberation of a great ai
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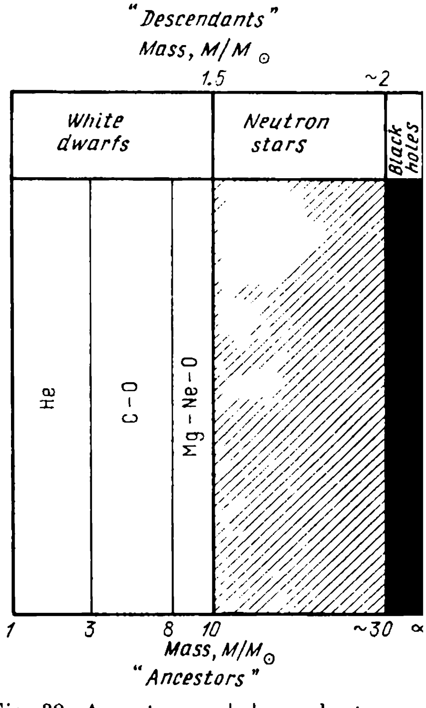


Fig. 39. Ancestors and descendants

If this happens, all that remair
star is a supernova explosion and
nebula.

Iron cores grow in stars with ma

$10M_{\odot}$. When the star collapses, the result is a neutron star. A neutron star's mass cannot exceed the Oppenheimer-Volkoff limit ($(2\text{-}3)M_{\odot}$). Finally, especially massive stars may turn into black holes.

These considerations allow us to classify stars into massive stars ($\geqslant 10M_{\odot}$) which produce neutron stars and black holes, and low mass stars which produce white dwarfs.

Such is the lifestyle of single stars or binary stars whose components are far apart. What happens to binaries in which the two components are close neighbours? Or in systems where mass exchange is possible? Evidently, the same thing, only with one reservation. The situation is radically different when one of the stars fills its Roche lobe and when mass exchange begins. The star losing its mass may become the less massive component. When the exchange starts, however, the star already "knows" what kind of descendants it can hope for. The type of compact star is determined by the star's initial mass. It is called the ancestor star.

Mass exchange in a massive binary saves it from destruction. The exchange, however, does not happen instantaneously, which means there must be binaries in our Galaxy in which the exchange is underway now. The discovery of such systems would be the best proof that the role change actually occurs the way we think it does.

Chapter 4

First Exchange

The Algol paradox indicates that star masses in binaries can change dramatically. This does not sound surprising today. The theory of stellar evolution demands that stars expand. On the other hand, celestial mechanics requires that matter leaving the Roche lobe is lost from the star for good. It is only logical that the mere combination of these two facts means that mass exchange between stars is a reality.

However, the Algol paradox and our theoretical arguments do not yet prove that mass exchange is a fact. What we need is substantial evidence. Astronomers have now managed to find undeniable evidence by catching a star "red-handed" in the process of mass exchange.

John Goodrike Again

On September 10, 1784, John Goodrike discovered β Lyrae, the second eclipsing variable star. Like Algol, this star is famous for its light curve. In contrast to Algol, though, the light curve of β Lyrae does not have even roughly flat parts.

It winks all over the place (Fig. 40). Between two successive eclipses its light curve is not constant, and when it attains maxima at phases 0.25 and 0.75, it falls rapidly. The flat part of the light curve corresponds to the moment we see both components of

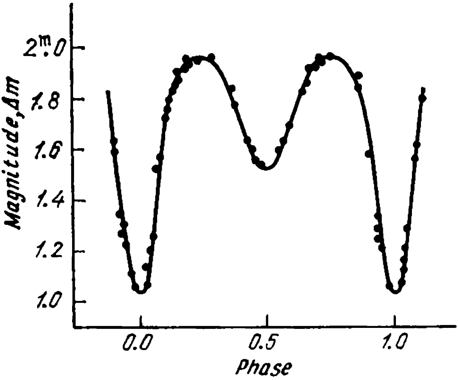
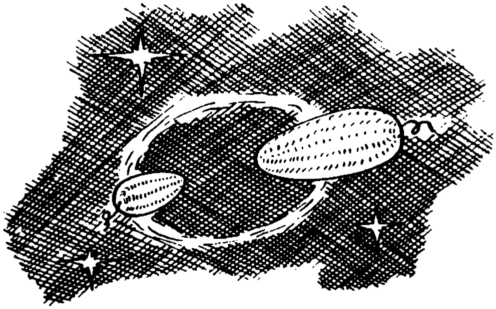


Fig. 40. The light curve of β Lyrae recorded at the Tien Shan station of the Sternberg State Astronomical Institute

the binary simultaneously. The light from a system is the sum of the light or, to be more exact, energy fluxes coming from the both stars. The period of variation of β Lyrae is 12.9 days, i.e. more than four times longer than that of Algol. It seems as if this system must be wider and its eclipses must be shorter. In fact, the stars of β Lyrae are both heavier and larger.

Do you remember Newton's argument with Cassini about the shape of the Earth (see Chap. 1)? The rotation of a single star about its axis flattens it at the poles. However, the revolution in a binary system pulls the stars along the line which holds them together; therefore, the binary's components are melon-shaped, i.e. triaxial ellipsoids. As a result of the orbital motion,



The ellipsoidal effect

the stars show different sides to the observer, which is why we see variations in the binary's light curve. This phenomenon is called the ellipsoidal effect. We may obtain this effect by examining a binary in which one star is shaped like a melon and the other one is extremely small (Fig. 41).

For simplicity, we assume that the binary's orbital plane is inclined at $i = 90°$. At phase 0, we see the star from its face and its light curve is at a minimum and the radial component of the star's velocity is zero. Then the star turns and the visible area gradually grows. The light curve

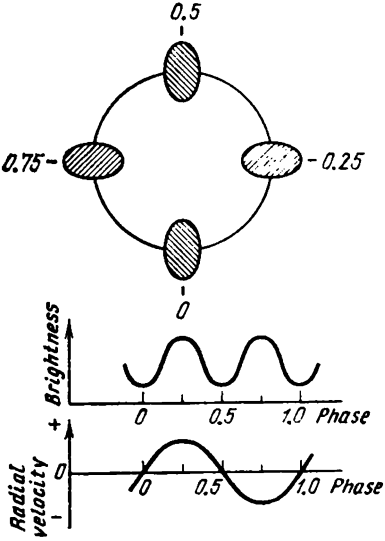


Fig. 41. A change in the light of a star caused by the ellipsoidal effect

increases and reaches a maximum at phase 0.25. At this moment, the star is seen from the side, its velocity is at a maximum and is directed away from us. In a quarter of the orbital period, the light curve again decreases to a minimum. Then the whole thing is repeated. In one period, the light curve rises twice to a maximum and twice falls to a minimum. For this reason, such a light curve is called a double wave.

Note that the reflection effect results in one wave per period and a maximum of light at phase 0.5. The ellipsoidal effect brings about a double wave and maxima at phases 0.25 and 0.75.

Yet the model curve in Fig. 41 is different from the observed curve (cf. Fig. 40). The depths of the minima especially are different. At the primary minimum, the binary's light curve falls to a magnitude of 4.2, while at the secondary minimum it falls to 3.9. But this may easily be explained by a partial eclipse of one of the binary's components. To sum up, the light curve of β Lyrae is a combination of two effects, eclipses and the ellipsoidal effect. The latter is governed by the degree to which the stars in a binary are flattened. The maximum elongation is achieved when the star fills the Roche lobe completely. Therefore, variations in light due to the ellipsoidal effect cannot exceed several tenths of a magnitude.

As I mentioned in Chap. 1, the shape of a star in a binary corresponds to an equipotential surface. If a star approaches the size of the Roche lobe, then its shape will resemble a pear rather than a melon. The side facing its neighbour differs in shape from the far side. This means that there will be a difference in brightness between the two sides. The star's spout (the area near the inner Lagrangian point) is colder than other parts of the surface. Therefore, the minima on the curve of the ellipsoidal effect are always different. (And what about maxima?)

By measuring the amplitude of the ellipsoidal effect, we can determine the extent to which the Roche lobe is filled by a star in a binary. In other words, we can determine the relative size of the star. An analysis of the light curve of β Lyrae shows that a brighter component is close (or, probably, equal) in size to its Roche lobe. It is reasonable to suspect it of mass transfer to the other star. If you study the spectrum of β Lyrae, the suspicion will grow into confidence.

The Spectrum of β Lyrae

The spectra of most stars, like that of the Sun, contain dark absorption lines. When we were discussing the Doppler effect, we said these lines resulted from the thin cold stellar atmospheres. You can observe these lines in the spectrum of β Lyrae too. However, there are also bright lines due to different chemical elements. These are known as emission lines. Like the binary's light curve, the emission lines and absorption lines are "moving" along the spectrum with the same period of 12.9 days. I hope you can see why. What is more difficult to explain is that the emission lines of different elements are "moving" in different phases, of which there are more than two. You get the impression that instead of a good old binary there is a horde of stars, which, of course, is impossible for how could they all rotate with the same rate.

The absorption lines, however, all are "moving" in the same phase. Characteristically, the star's radial velocity at the primary minimum becomes zero and then the velocity becomes negative. This means that the star, whose lines we are observing, was moving away from us before the primary minimum; then it began moving towards us. In other words, the star is being eclipsed. This is only natural because it is the brighter star, whose lines must be visible, that is eclipsed at the primary minimum. Until recently, however, nobody could have detected the lines of the second star.

Researchers determined the spectral class of the bright component of β Lyrae from the absorption lines; the component happened to be of spectral class B8. The bright star's mass could then be determined from the mass-luminosity relation (see Fig. 32) for main-sequence stars. It is approximately $3M_{\odot}$. The mass function determined by the radial velocity curve was surprisingly large, approximately $12M_{\odot}$. Remember the remarkable feature of the mass function (see Chap. 2): the mass of the second star cannot be less than the mass function. It means the second star is much more massive. There was the puzzle: the second star is nearly four times the size of the first and yet the binary's spectrum contains none of its lines.

Consequently, the observation data brought the researchers to stop. Two most important issues had to be tackled: what was the origin of the emission lines and why doesn't the more massive star give any spectral lines?

Gravity Wind

When we discussed the measurement of the stars' radial velocities (see Chap. 2), we saw how absorption lines appeared in a star's spectrum. Now it is clear that if we place cold semitransparent gas between us and a hot body giving the Planck spectrum, the latter will contain absorption lines making it look "chipped" (Fig. 42*a*; see Fig. 23).

Now imagine that we gradually heat up the gas hiding the star. In the heated gas, atoms collide more frequently and with a greater vigour. The atoms are mutually excited as the kinetic energy turns into

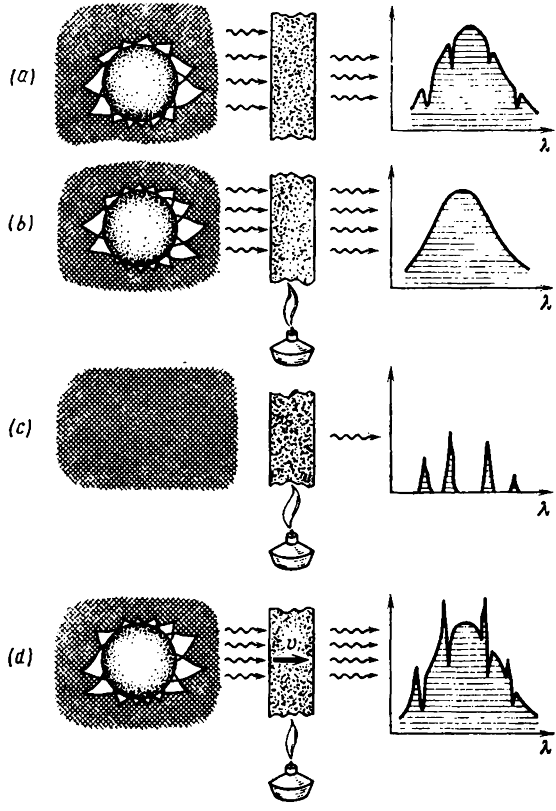


Fig. 42. The formation of emission lines in a star's spectrum

the energy of the electrons. Electrons which have received energy are "thrown" up to the upper energy levels. However, they cannot reside there for long and in a while (to be more exact, in about 10^{-8} s) they will fall down the potential well of the electrostatic field of the nucleus after giving off a quantum of light. Since the gas is not very dense, the quantum will leave without delay and cool the gas by taking up some of its energy. We shall make up for this loss of energy by further heating. What will happen next?

In accordance with the quantum mechanics laws, a hot gas radiates only the same lines it absorbed from the star's radiation. It is clear now that, as the gas gets hotter, the "chips", i.e. the absorption lines, will become filled with radiation and become less deep. If we increase the incoming thermal energy and thus continue to heat the gas, the "chips" will be completely filled and we get a spectrum without any lines at all (Fig. 42*b*).

Now we take the star away. The continuous radiation will disappear and the spectrum will turn into an irregular fence of bright emission lines replacing the absorption lines. In this way, a transparent gas heated to a temperature which still permits the existence of neutral atoms (10000 K) produces a spectrum that is almost completely composed of a fence of lines. True, at a temperature of 10000 K free electrons also exist. A free electron, i.e. one outside an atom, can emit a quantum of any frequency. At a temperature of 10000 K, however, the electron's energy is so small that, as it comes a little closer to an ion, it is captured (or recombines), and later it emits the whole of its energy only on the frequencies of the lines. Therefore, the contribution of the continuous spectrum will be small (Fig. 42*c*).

It is obvious that such a spectrum differs greatly from the Planck spectrum of a blackbody. It is easy to see why. The gas under study is optically thin. A new photon undergoes only several scatterings and absorptions before it leaves the gas. The radiation does not have enough time to attain the temperature of the gas, which is why its spectrum looks like an irregular fence.

Try to imagine another thing (Fig. 42*d*). Suppose we put the star back to its initial position and make the gas move with respect to the star. For instance, suppose the gas is moving towards us. Due to the Doppler effect, all the emission lines produced by the gas will be shifted to the violet end of the spectrum, while the absorption lines will stay where they are in Fig. 42*a*. The star's spectrum thus has both emission and absorption lines for the same atomic transition. If the hot gas moves in a circle, there will be a periodic shift in the emission lines with regard to the absorption lines in the spectrum.

This accounts for the "moving" of the lines in the spectrum of β Lyrae. Only the emission lines of different elements move differently depending on a phase. The radial velocity curves for the different lines varies in amplitude between 80 and 360 km/s, which is due to the presence of several streams of optically thin gas, each with its own temperature. The lines of the easily excitable elements will form in the colder streams while the lines of the elements which need more energy to be excited will form in the hotter streams. It might be the same stream which varies in velocity and temperature.

Where do gas streams come from? As the curve of β Lyrae shows us, the brighter star is close in size to the Roche lobe or, probably, fills it completely. What we have to do is to put two and two together. The material in the brighter star near the star's spout (the inner Lagrangian point) is captured by the gravitational field of the darker star. An accelerated gas stream stretches out and rushes towards the darker star. We call this a gravity wind, for what is a wind on the Earth if it is not a stream of gas caused by a difference in pressure. Similarly, in a binary the wind is driven by gravity, which is the kind of wind "blowing" in the β Lyrae binary (Fig. 43).

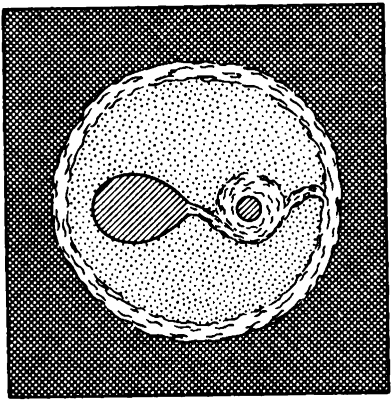
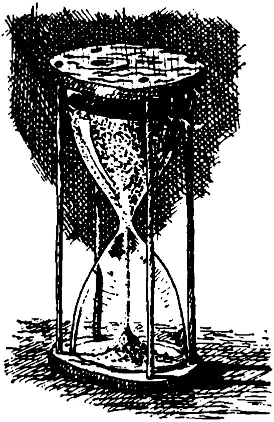


Fig. 43. Gas streams in the β Lyrae system



An exchange

In this way, the familiar variable star John Goodrike discovered at the end of the 18th century has proved to astronomers that mass transfer really happens in the world of binaries. The Algol paradox gave us a "hint", while the emission lines of β Lyrae are the substantial evidence.

Another convincing example of an intense mass exchange is given by RX Cassiopeiae, a binary, which was thoroughly studied by Dmitry Martynov, one of the first Soviet astronomers to study binaries. The list of examples is still incomplete.

A Peculiar Device

It is well-known that the liquid levels in communicating vessels are the same. This phenomenon can be seen in a laboratory device which looks like two vessels linked by a connecting tube. For convenience, the tube should be at the bottom to make the communication between the vessels independent of the quantity of water poured into them. Suppose an eccentric or incompetent glass blower had fixed the connecting tube at the upper end of the device. Before you smile, let me tell you that the device demonstrates how mass transfer occurs in a binary. If the vessels are different in height, so much the better; the narrower vessel should be a little higher (Fig. 44). The connector acts as the spout near the inner Lagrangian point. The upper edges of the vessels are like the outer Lagrangian points (L_2 and L_3, see Fig. 13). Note that the point L_2 is closer to the less massive star and the level of its potential is lower than at the point L_3. By pouring water

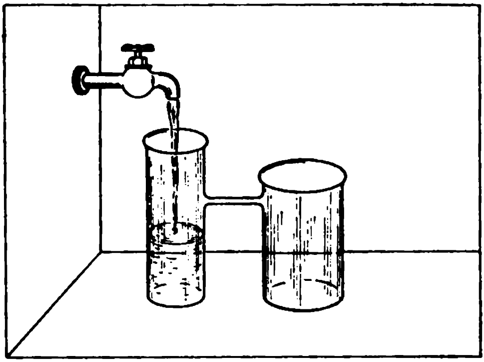


Fig. 44. An experiment illustrating mass transfer in a binary

into the left-hand vessel (see Fig. 44) we simulate the nuclear evolution of a binary. As long as the water does not reach the connector, the vessels are disconnected and the water levels are different. A gradual rise of the water in the left-hand vessel simulates the expansion of the more massive star during nuclear evolution. The second star, which is lighter, remains practically the same. As soon as the water reaches the connector (the Roche lobe is filled), the vessels become connected and the water levels in each vessel begin to equalize. If the incoming stream of the water does not stop, the water levels will equalize and eventually the water will fill the right-hand vessel, which is lower, and splash onto the table. In other words, material will leave the binary system. It is clear that, however perfect, two vessels are an inadequate analogue of a binary system. Mass exchange is a complex process and its gas dynamics is still a subject for research. A laboratory device can give us a correct idea of how it all happens, but a more detailed study will take more time.

Suppose a star fills its Roche lobe. If you give a particle a push near the Lagrangian point, it will slide into the other star's Roche lobe. Note that at a Lagrangian point the resultant force of three (not two!) forces is equal to zero. Two of the forces are the stars' gravity and the third is centrifugal (don't forget we are inside a rotating coordinate system). If the particles sliding from the Lagrangian point could avoid mutual interaction, each would move along its own intricate trajectory (see Fig. 10). But star material is a gas whose particles collide. Random motions are neutralized in collisions and disappear turning into heat. What remains is the motion of particles from one star to another. Thus the gas forms a stream, otherwise known as a "gravity wind". In order for the stream to be sufficiently dense the star must overfill its Roche lobe a little (i.e. the water level in the left-hand vessel must be a little higher than the connector).

What is the gas stream up to? A qualitative picture of its motion is as follows. A gas stream with a thickness of about 0.1 of the radius of the outflowing star cannot find its way directly to the other star. This is easy to see if we adopt a reference frame fixed to the second star. The outflowing star and the gas stream revolve about us with a binary star's orbital period. It follows that the material of the stream has an angular momentum in relation to us. In other words, it strikes but misses. The accumulation of matter due to gravity is called accretion and the star on which the matter accumulates is called the accreting star. The gas stream is turned away by the accreting star's gravitational field. If the second star is far from filling its Roche lobe, the gas stream does not hit it directly but wraps around it in a gaseous ring or a disc-shaped envelope. At different distances, the rotation in the envelope occurs with different angular velocities. Such a rotation is known as differential. Friction between neighbouring layers causes an exchange of angular momenta. The ring turns into a disc. The inner layers give their angular momentum to the outer layers and so approach the accreting star. Eventually, the matter settles on the star's surface.

A Strait-Jacket for a Star

A star that gives off part of its mass is close in size to the Roche lobe. The star's surface is, in fact, the surface of the Roche lobe. The situation, it seems, should change shortly. A star which has lost part of its mass and become smaller should shrink to maintain hydrostatic equilibrium. The smaller the mass of a nondegenerate star, the shorter its radius. The star adjusts to fit a new mass almost instantaneously. For example, it would take the Sun only 20 min. That is when a mass transfer would seem to come to an end.

This is not always so. As the star loses its mass, the relation between the masses of the binary's components changes and so does the size of the Roche lobe. Don't forget that the star nuclear evolution which is accompanied by an increase in the star's radius causes the star to fill the Roche lobe. It is the combined effect of these three processes that governs the rate and duration of matter transfer.

Will the Roche lobe size vary much? For simplicity, let us assume that one star's matter is completely transferred to the other star. This simplification allows us to solve the problem without resorting to higher mathematics. All we need is the law of the conservation of the binary's orbital momentum because the binary does not lose mass. If a mass exchange does not cause a loss of matter by the binary, then the exchange is said to be conservative.

Assume that the matter is transferred from the more massive star to the less massive companion. Now suppose we transfer one gram of matter from the larger star and put it carefully on a smaller star. The latter has the greater orbital momentum, which makes it chief (see Chap. 1). This transfer reduces the average (per unit mass) orbital momentum of the less massive star moving it a little closer to the larger one. It follows that the mass transfer from the larger star to the smaller one reduces the distance between them! The binary shrinks and the Roche lobe becomes smaller too. However, a star that has lost mass will cease to be in thermal equilibrium. It radiates energy which does not correspond to its mass. The thermal equilibrium is established much more slowly than hydrodynamic equilibrium but more quickly than the star's nuclear evolution (see formulas (7), (10), (11)).

The reduction in the size of a star is, therefore, made up for by the reduction in the size of the Roche lobe. The star loses mass for a period of the order of its thermal timescale remaining for that time in the "strait-jacket" of the Roche lobe. For massive stars this period is about 10^4-10^5 years. The rate of mass exchange in such systems is about 10^{-4}-$10^{-3} M_{\odot}$ per year. This is ten billion times more than the rate with which the Sun loses mass due to the solar wind. In contrast to the solar wind, the gravity wind looks like a hurricane.

Now suppose the less massive star fills its Roche lobe. In this case, matter with a larger angular momentum settles on the star with the smaller angular momentum, thus increasing the latter's average angular momentum. The binary "spreads out", and the Roche lobe expands. If the mass transfer is too intense, the Roche lobe will tear off from the star and the mass exchange will come to an end. It will resume once the nuclear time expires and the expanding star again fills the Roche lobe. In fact, the mass transfer may not be quite so intense, and the star's size may be kept equal to the Roche lobe size. The star again finds itself in the "strait-jacket" of the Roche lobe. However, the exchange proceeds on the nuclear timescale rather than on the thermal timescale (see formula (10)).

The Second Puzzle of β Lyrae

β Lyrae has another puzzle. The emission lines convinced us that a mass exchange is a reality, but it wasn't clear why the more massive star doesn't show up in the binary's spectrum? The absorption lines in the system belong to the less massive hot star of spectral class B8. The mass function estimated from these lines puts a lower limit on the mass of the invisible satellite of $12M_{\odot}$. This is nearly four times the mass of the B8 star. It is impossible for such a star not to show itself in the spectrum. Note that the luminosity of a regular star is approximately proportional to the cube of its mass (see Chap. 3). With a mass ratio of 4 to 1, the luminosity ratio should be 64 to 1 in favour of the more massive star!

How do we account for this? The Algol paradox brought us to the idea that a change in roles was possible. Where will the paradox of β Lyrae take us? The most radical astronomers were prepared to believe that the more massive star in this system is a black hole! We don't see it because it is black. This is absolutely wrong, and as we are going to see, a black hole in such a binary would be much brighter than many "white" stars.

Another hypothesis is more promising. The mass-luminosity relation is applicable to main-sequence stars, i.e. stars in hydrostatic and thermal equilibrium. Is it possible that the second darker star in the β Lyrae system has yet to "settle down" after the violent transfer of matter from its neighbour? Before the exchange it was less massive and emitted little energy. Now it is more massive and although energy generation in the centre has accelerated we shall only learn about it a million years (the thermal time) from now. There's a dark massive satellite for you! It is like a huge dinosaur which tries to scratch its ear with a tail that was bitten off long ago.

After the Exchange

A star which filled the Roche lobe rapidly "loses weight". The calculations concerning

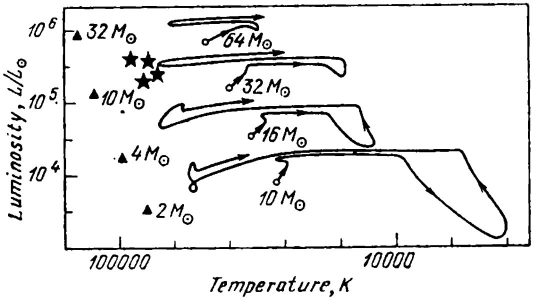


Fig. 45. The evolution of stars after a great loss of mass (★ shows the initial positions of the stars on the main sequence; ▲ labels the positions of purely helium stars)

the evolution of such stars were made in the 1960s. The results in the form of evolutionary tracks on the H-R diagram are shown in Fig. 45. As the star loses mass, deeper and deeper layers are exposed. The longer the star has lived before filling its Roche lobe and the more massive it is, the more advanced its nuclear evolution is and the heavier are the elements that have burnt within it. Mass exchange in a binary strips away the upper, unburnt hydrogen envelope. What remains is a star with an anomalous chemical composition and consisting almost wholly of heavier elements. Mass exchange terminates when the hydrogen finishes and helium starts burning in the star's centre. The star's radius reduces dramatically and the star is torn off from the Roche lobe. This is how helium stars are born.

It is possible that the stars discovered by the French astronomers C.J.E. Wolf and G. Rayet about 100 years ago were born in the same way. The spectra of these stars are quite astonishing (Fig. 46). They consist of not a fence but a forest of emission lines of helium and other heavy elements. Some of the lines are as wide as several nanometres. This indicates a rate of expansion of several thousands of kilometres per second.

In the early 1920s, the English astronomer Carlyle Beals surmised that the properties of Wolf-Rayet stars could be explained by a powerful isotropic flow of matter from the star's surface (Fig. 47). The Doppler effect broadens the lines in the spectrum. Thus the outflowing matter screens the light from the star itself. There are no hydrogen lines in the spectra of Wolf-Rayet stars.

To explain why stars are different (see Chap. 2), I have already emphasized that

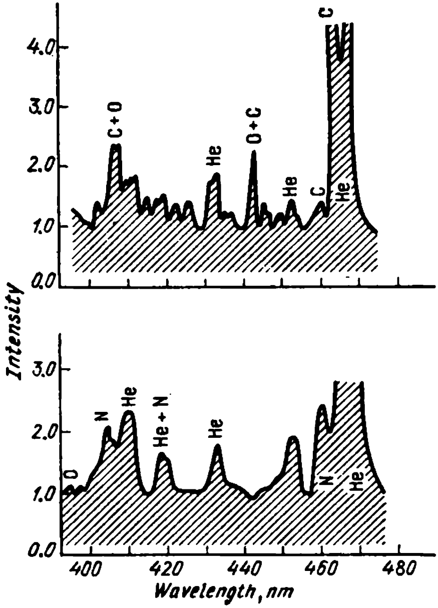


Fig. 46. Two typical spectra of Wolf-Rayet stars

it is their temperatures and not the chemical composition of their atmospheres that matters. If we keep this in mind, it must mean that there are no hydrogen lines in Wolf-Rayet stars because the situation is unfavourable for exciting these lines. But it is possible that there are no hydrogen lines solely because there is no hydrogen.

A helium star of the same mass as a hydrogen star is smaller. A helium star with

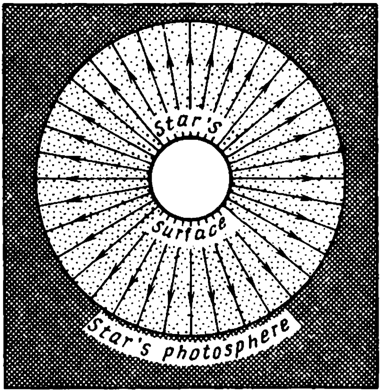


Fig. 47. The surface of the Wolf-Rayet star visible in lines is much larger than it actually is

a mass of $10M_{\odot}$ should have a radius of (2-3) $R_{\odot}$, i.e. about 3-5 times smaller than that of a hydrogen star. How do we estimate a star's radius? Not much of its surface can be seen, nor does its spectrum yield much for it differs too greatly from that of a blackbody. If a Wolf-Rayet star is a part of an eclipsing variable system, then its size can be estimated from its light curve.

Fortunately, a number of such eclipsing variable systems can be observed. The best-

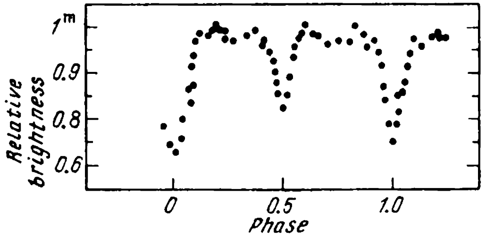


Fig. 48. The light curve of V 444 Cygni

studied one is V 444 Cygni (here V stands for "variable"). Its light curve is shown in Fig. 48.

Since a Wolf-Rayet star is wrapped into a large semitransparent envelope, its size cannot be determined by a light curve using traditional methods. In the early 1970s, Soviet astrophysicists used a new method to reconstruct the parameters of the V 444 Cygni system from its light curve. It turned out that the Wolf-Rayet star has a radius of (2-3) $R_{\odot}$. This means that Wolf-Rayet stars are helium stars. Another three eclipsing binaries with Wolf-Rayet stars were examined in later years and this research has proved the helium hypothesis.

As heavy elements burn out, a star evolves ever more rapidly. The lifetime of a helium star or, in other words, the nuclear time for helium is about 100 times shorter than that for hydrogen. The second star, however massive it gets due to a change of roles, is still on a "hydrogen diet" and therefore cannot catch up with the first one. It takes a helium star inhabiting a massive binary system several hundreds of thousands of years to explode and thus give birth to a neutron star or a black hole. In less massive binaries, white dwarfs appear quietly.

The Story Will Be Continued

In Chap. 2, I said that the mechanism of a role changing is like a mine provided with a delayed-action fuze. This mechanism is very important in the evolution of a binary. Suppose there is no mass exchange at all and the more massive star stays as such. If its core collapses, practically the whole of the binary's mass will be ejected from the binary because neutron stars are 10-20 times lighter than the massive star. Thus the system is doomed to the loss of more than a half its mass and to disintegration.

Therefore, but for the change of roles, the system would cease to exist as a binary. It is different when the exchange results in the explosion of the less massive star which cannot shake off more than a half the binary's total mass. This leads to a new type of binary in which an ordinary star coexists with a neutron star or, perhaps, a black hole. Note that any massive system living according a scenario with a role changing will end up with such an exotic combination. How many stars of this type are to be found in the Galaxy? Can we discover them? These questions intrigued astronomers in the 1960s. At the time, few suspected that scores of them were above their heads.

How to Count Stars

Imagine you are queuing for an interesting exhibition at a museum. The line is long and is moving slowly. You are cold and bored, and having nothing better to do, you wonder how many lucky ones have already got inside the museum. You have been waiting for a long time and see that the situation is stable. In this case, stability means that the number of people leaving the museum is equal to the number of people entering it. If this assumption were not true, the museum would be either empty or overfull.

So how do you count the people inside the museum? The simplest way would be to wait until you get inside and quickly count them all. But it is not a good plan. First, it is technically impossible; second, you have come to see the exhibition, not to count people.

There is another way. You estimate the average number of people entering the museum. Suppose it is 100 people per hour. (The number itself "warms you up".) To while away the time, you go to the exit to find out how much time it takes people to see the exhibition. By averaging their replies, you find that they spent, say, four hours. What you know now is enough to get an answer to your question. The number you need is the number of people per hour times the duration of their stay inside:

100 people per hour $\times$ 4 hours   400 people.

It is easy to see that this solution requires no information about the structure of the museum. The only important assumption we made is that the flow of visitors has stabilized. We call this the steady-state condition.

The same technique is widely used in astronomy. Suppose you know how many stars of a given mass are born in the Galaxy per unit time. This quantity may be termed the star birth-rate. It is dependent on the mass of the stars and is called the Salpeter function. Edwin Salpeter first derived this function in the 1950s by the application of statistical methods to a great number of observations. For our Galaxy the number of newly born stars N (M) with a mass exceeding M is

$$N(M) = 0.7\,(M/M_\odot)^{-1.35} \text{ stars per year.} \quad (14)$$

According to this formula, the number of stars with a mass greater than $10M_\odot$ that appear annually is 0.03, i.e. one star every 30 years, while the corresponding number for stars with a mass of more than $M_\odot$ is 0.7 per year. It is clear that the birth-rate falls rapidly with mass.

Now it is not difficult to count how many stars with a certain mass exist in the Galaxy at one time. Assume that we are interested in main-sequence stars with masses exceeding $10M_\odot$. The lifetime of a star on the main sequence depends on the nuclear time for hydrogen (formula (10)). For stars with a mass of about $10M_\odot$ this is 10 million years. We multiply this by the star birth-rate (0.03 per year) and see that there are approximately 300000 such stars.

It is easy to calculate the number of supergiants too. They have masses in excess of $10M_\odot$ and an average lifetime 100 times shorter than the nuclear time. This means that in the Galaxy there are about 3000 O-B supergiants, i.e. supergiants of spectral classes O and B. We have, it is true, started from the assumption that the situation in the Galaxy is steady-state.

Now we can find the number of binaries with relativistic stars (neutron stars and black holes) in the Galaxy. Due to the change of roles, practically every close binary gives birth to such a binary system. How long does such a couple live? We surmise that it lives for as long as the normal star is on the main sequence. The exchange increases the mass of a normal star from $10M_{\odot}$ to, on average, $20M_{\odot}$; therefore, we should use nuclear time for $20M_{\odot}$, i.e. about 5×10^6 years.

Such stars are born in the Galaxy every 30 years, half of them being binaries. Don't forget that a binary is a two-star arrangement, and we must half 30 years. Eventually, we conclude that a binary we are interested in appears every 50-100 years. We multiply this birth-rate by 5×10^6 and find that there must be 50-100 thousand massive stars with relativistic components in the Galaxy.

Well, the story is really to be continued.

Chapter 5
Massive X-ray Binary Stars

The only possible outcome of stellar evolution is the depletion of nuclear sources of energy. Sooner or later, any star will eventually turn into a compact star, i.e. a white dwarf, a neutron star, or a black hole. Massive stars, i.e. the ones whose mass exceeds $10M_{\odot}$, evolve into neutron stars and black holes. These compact stars may be called relativistic. Their total energy (with their rest mass taken into account) Mc^2 is comparable with gravitational energy GM^2/R. Nearly all the energy in a black hole is concentrated in the gravitational field, while 10-30% of the energy in a neutron star is gravitational energy.

Although it became clear in the 1930s that neutron stars and black holes could exist, no attempt was made to discover them experimentally during the next 20-30 years. I shall now explain why the situation changed in the 1960s.

"M with a Dot"

The reason is to do with the size of neutron stars and black holes. Although having the mass of a star, these objects have radii of only a few dozen kilometres.

According to the Stefan-Boltzmann law,

the luminosity of a hot body is proportional to the area of the radiating surface and the fourth power of its temperature. The area of the surface of a neutron star with a radius of 10 km is $(700000/10)^2$, or about 5 billion times less than that of the Sun. Hence, a neutron star having the same temperature as the Sun would be 5 billion times weaker. This difference in brightness corresponds to 24 magnitudes (see formula (3)). The absolute magnitude of a star, i.e. the magnitude it would have if it were 10 parsecs (32.6 light-years) away, would be 29^m. Note that the best telescopes available today are limited to magnitude 25. You would have to be very optimistic to look for such a faint star. The situation is still worse with black holes, which not only do not radiate anything at all, but also absorb everything within the reach. Nobody wanted to undertake something as effort-consuming as it was hopeless. There were only a few papers on neutron stars and black holes from around the world before the 1960s. It is surprising they appeared at all. For example, in 1949, the Soviet astrophysicist Samuil Kaplan wrote a paper on the motion of a test particle in the gravitational field of a black hole. It is interesting that at the time he was working at the observatory of Lvov University whose telescopes were much worse than the contemporary standard.

The situation changed dramatically in the early 1960s when quasars and the first X-ray sources were discovered. Quasars (quasistellar objects) look in the visible region of the spectrum as stars, but their luminosities are incredible. They are 10^{13}-10^{15} times brighter than the Sun and many thousands of times brighter than whole galaxies. Galaxies radiate the energy produced by nuclear sources in stars and are much larger than quasars. This means that quasars must be powered by some other, more efficient energy sources.

In 1964, the Soviet physicist Yakov Zeldovich and the American astrophysicist Edwin Salpeter working independently discovered a source of energy which is hundreds of times more effective than fusion reactions. To realize this method, you need a relativistic star whose gravitational field does the work, and the surrounding matter is used as a fuel.

Suppose the surrounding matter falls freely onto the star's surface. Moving like a test particle with zero energy (see Chap. 1), this matter will fall onto the surface with the escape velocity. The kinetic energy of particles per unit mass equals in this case $v^2/2 = GM/R$. Assume that all kinetic energy turns into heat when the matter hits the surface and is radiated into the surrounding medium. It is convenient to measure the amount of matter attracted by gravitation (i.e. accretion) by the quantity of matter falling onto the star's surface per unit time. This quantity is otherwise known as the accretion rate, and it shows how rapidly a star's mass changes in time. The rate of change of some quantity is called a derivative. To distinguish between the derivative and the quantity, a dot is placed above the letter designating the quantity. (This notation and the idea of a derivative itself is due to Isaac Newton.) Thus, the derivative of distance X is written $\dot{X}$. This is a speed. The rate at which a star either loses or gains mass is designated $\dot{M}$. This notation is so widespread that the temptation to use it in a text for the layperson is too great, but it does not demand any special knowledge. It is enough to understand that a letter with a dot shows the rate of mass change.

So each second $\dot{M}$ kg of matter falls onto the star's surface. Each kilogram has a kinetic energy of GM/R_*, where R_* is the star's radius. If all this energy is radiated, the star's luminosity will be

$$L = \dot{M}\frac{GM}{R_*}. \tag{15}$$

For neutron stars, $GM/R_* \simeq$ (0.1-0.3) c^2, i.e. $L \simeq$ (0.1-0.3) $\dot{M}c^2$. Consequently, 10-30% of the total rest energy of the fuel is radiated. This is about 100 times more than the fraction of the rest mass produced by the burning of hydrogen into helium.

But what happens around a black hole, which has no hard surface? The falling matter has nothing to hit. The answer was found by Zeldovich. We "make" the matter

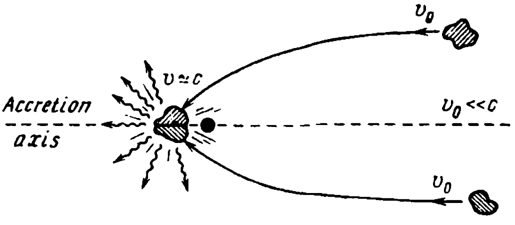
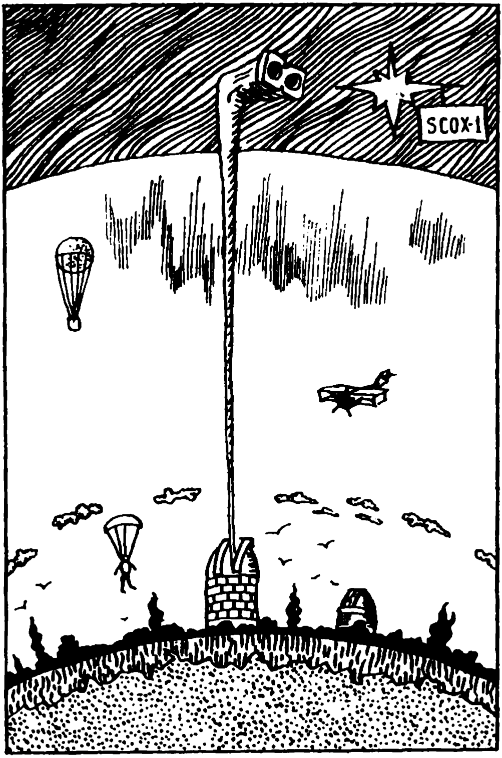


Fig. 49. A gravitational "accelerator". Collision with a relativistic star will liberate up to 10% of the objects' rest energy

collide with itself! Imagine two particles falling onto a black hole symmetrically (Fig. 49). They accelerate in the hole's gravitational field and eventually collide on a certain axis called an accretion axis. The collision must occur as close to the black hole as possible. Then the velocity of the colliding particles will approach the velocity of light. The collision will release 10% of the rest energy of the particles. It should be noted, however, that the collision should not occur too close to the black hole. The energy gain in this case will not be impressing because the hole itself will soak up most of radiation.



The discovery of X-ray stars

In his 1964 paper, Zeldovich stressed that a very powerful source of energy would be a binary where the second star supplies the matter fuel for the gravitational machine.

A combination of the idea of accretion by a relativistic star and the concept of a binary system stimulated both theoretical and experimental thought.

"Brighter Than a Thousand Suns"

All ordinary stars lose matter irrespective of whether they are a part of a binary system or not. The first space flights showed that the Sun is a source of a continuous flow of charged particles travelling at several hundreds of kilometres per second. This flow of plasma is called the solar wind.

The same quantity $\dot{M}$ may be used to describe the power of this flow. The rate at which matter flows from the Sun is about $10^{-14} M_{\odot}$ per year, so it halves the mass of the Sun over a period of 10^{14} years, i.e. much greater than the age of the Sun. So we conclude that the solar wind does not affect the Sun's evolution. Similar winds emanate from other stars. The larger the star, the stronger its wind. The flow rate for a blue supergiant is $10^{-6} M_{\odot}$ per year, while that of a Wolf-Rayet star is approximately $10^{-5} M_{\odot}$ per year.

Let us determine the power of a gravitational machine if its efficiency is 10%:

$$L = 0.1\dot{M}c^2 \simeq 15000L_{\odot}\frac{\dot{M}}{10^{-8}M_{\odot}\text{ per year}}. \quad (16)$$

It is easy to see that if even only 1/1000th of the matter in the wind flowing from a blue supergiant falls onto a relativistic star, the new source will flare up "brighter than a thousand suns".

How can a tiny (by area) neutron star radiate such great amount of energy? Obviously, only due to a high temperature. We have mentioned that the area of a neutron star is 5 billion times smaller than that of the Sun. According to the Stefan-Boltzmann law, a star which is 1000 times brighter than the Sun must have a temperature $\sqrt[4]{5 \times 10^9 \times 1000} \simeq 1500$ higher than the Sun's. The temperature of a neutron star must reach several dozens of millions of kelvins. Photons emitted by a body with such a temperature have energy of about 1000 eV This is in the X-ray range of the spectrum, and the Earth's atmosphere is opaque to quanta with such energy.

The atmosphere consists of neutral atoms. Neutral atoms can absorb light only in narrow lines of the spectrum, in a transition from one level to another. This is only true until the energy of the quantum entering the atmosphere is not sufficient for ionizing the constituent atoms. The ionization energy for different atoms amounts to dozens of electronvolts. However, an X-ray quantum has hundreds of times more energy. So as they pass through the air, X-rays ionize its atoms and are absorbed by it. That is why you must go beyond the dense layers of atmosphere to register X-rays.

In 1962, a group of American astrophysicists headed by Riccardo Giacconi put equipment for observing X-rays into orbit aboard the Aeroby-150 rocket. The equipment consisted of three Geiger counters capable of detecting photons with energies varying from 1600 to 6200 eV.*

The history of X-ray astronomy and that of atomic physics are closely interwoven, both theoretically and experimentally. The Geiger counter is little more complicated than the electrometer, which helped discover cosmic rays. The operational principle of the Geiger counter is based on the ability of X-ray photons to ionize gas.

Imagine an X-ray quantum being absorbed between two electrodes to which a high voltage is applied (Fig. 50). The quantum spends its energy to ionize an atom. The free electron then accelerates in the electric field and ionizes other atoms. Thus the number of electrons starts snowballing and a current emerges. This counter is called a proportional gas-discharge counter. It is

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* X-rays radiated by the Sun were observed in 1948 using a rocket which climbed to an altitude of 200 km.

proportional because the output current is proportional to the energy of the absorbed photon. (The more energy a photon has, the more free electrons are produced.) The coun-

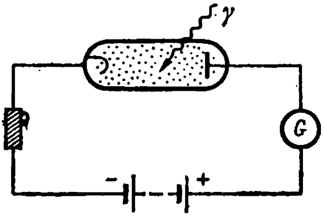


Fig. 50. A Geiger counter block diagram

ter is placed in a protective housing with a window to enable it to work in a particular direction.

As soon as a rocket carrying equipment is beyond the atmosphere, it starts sending signals showing evidence of variable X-ray radiation. The period of the X-ray radiation was exactly the same as the period of the rocket's rotation about its axis. The rotation of the rocket made it possible to determine, however roughly, the direction towards the source. The radiation was coming from the Scorpius constellation. In this way, astronomers discovered the first X-ray source beyond the Solar System, namely, Scorpius X-1 (here X comes from "X-rays"). The X-ray radiation was so powerful that it took astronomers some time to dare suggest that it was, in fact, located beyond the

Solar System. If we surmise that the distance between the Earth and Scorpius X-1 is 1000 light-years, then its luminosity will exceed that of the Sun by dozens of thousands of times.

In 1967, Yakov Zeldovich, Igor Novikov, and (independently) Iosif Shklovsky suggested that Scorpius X-1 is a binary system in which a neutron star is intercepting the matter flowing from a normal star and radiates in the X-ray range. It was a hypothesis unsupported by rigorous proof.

While X-ray astronomy was taking its first steps, radio astronomers ran into neutron stars (we discussed radio pulsars in Chap. 3). The discovery whipped up work by theorists. In 1967-1971, a large group of young Soviet astrophysicists inspired by Zeldovich launched a wide-scale assault against the problem of accreting relativistic stars.

In 1969, the formation of the spectrum of an accreting neutron star was studied for the first time. Neutron stars were predicted to radiate X-rays, and, as a first approximation, a neutron star without a magnetic field was considered. Radio pulsars, however, are direct evidence that neutron stars, in fact, possess magnetic fields which play a vital role in matter accretion.

The accreting matter in a binary system is plasma, which is an excellent conductor of electricity. At the accretion rate typical of a binary, a magnetic field affects the motion of the matter over several thousands of kilometres, i.e. over distances several hundreds of times greater than the size of a neutron star itself. When affected by a magnetic field, matter moves anisotropically, which means that a neutron star will radiate anisotropically too. The star's own rotation will cause the radiation to fluctuate!

At almost the same time, Zeldovich's pupil Viktory Shvartsman boldly suggested that X-ray pulsars should be found in close binary systems. His argument was that if a radio pulsar (for instance, the radio pulsar in the Crab Nebula) were placed in a binary system, the pulsar would radiate (eject) powerful fluxes of electromagnetic waves and relativistic particles (Fig. 51*a*). The pressure produced by the ejected fluxes would be so high that all the matter in the stellar wind would be "swept out" of the binary, thus making accretion impossible.

This cannot go on for ever. The pulsar will lose its rotational energy, and will rotate more slowly. As this goes on, its luminosity and the pressure ejecting the stellar wind will lower. Obviously, there will come a moment when the radio pulsar will "fade" to a degree at which the accreting matter attracted by gravitation will rush to the neutron star. Although the pulsar's radiation has "faded" accretion is still impossible. The reason for this is the rapidly rotating magnetic field of the neutron star.

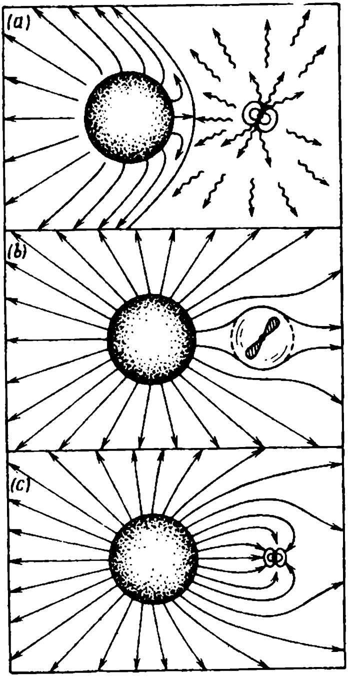


Fig. 51. Three states of a neutron star in a binary system: (*a*) an ejecting pulsar; (*b*) a "propeller"; (*c*) an accreting neutron star

Like an enormous propeller, it scatters the matter and does not let it fall (Fig. 51*b*). This effect was later called the propeller effect by Andrei Illarionov and Rashid Syunyaev. Whilst repelling matter, the pulsar continues decelerating until accretion is possible (Fig. 51*c*). The matter rushes to the neutron star's magnetic poles, and the result is a terrific outburst of energy. An X-ray pulsar powered by accretion flares up.

The scenario seemed too bold, and many experts were critical of it. At the same time, a young astrophysicist named Nikolai Shakura studied disc accretion on a black hole and proved that a black hole in a binary system must be an X-ray source. Within a year these results were all brilliantly confirmed by observations conducted from Uhuru, an American X-ray satellite.

The breakthrough made by Soviet astrophysicists prior to the launch of Uhuru correctly explained nearly all the properties of the X-ray sources discovered in the 1970s. Suffice it to say that all the research on accreting neutron stars before the launch of Uhuru was done in the USSR.

Uhuru

On December 12, 1970, Uhuru, the first X-ray satellite was launched from Kenya. The Swahili word "uhuru" means "liberty". The satellite carried X-ray counters to record an X-ray source 10000 times as weak as Scorpius X-1. This satellite allowed humanity to see clearly in the X-ray range.

Within a few years of observation, this satellite discovered more than 300 X-ray sources. The brightest X-ray pulsars turned out to be of especial interest to the experts. As predicted by Soviet astrophysicists, some of them were fluctuating. One of the first pulsars to be discovered was Centaurus X-3. Its fluctuation period is 4.8 s. The

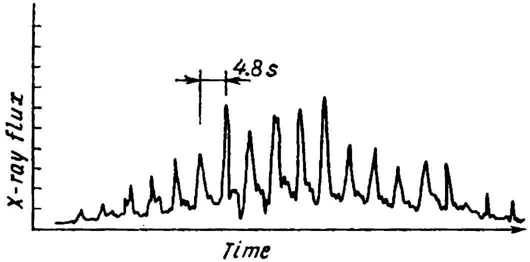


Fig. 52. Recording of X-ray pulses coming from the pulsar Centaurus X-3 (the modulation is caused by the receiver's rotation)

light curve of an X-ray pulsar greatly differs from that of a radio pulsar (Fig. 52). The light curves of radio pulsars resemble a broken comb with very fine pulses. The pulses of an X-ray pulsar are less distinct and look like the edges of an accordion's bellows. This means that the "lighthouse" beam of an X-ray pulsar is much wider than that of a radio pulsar.

Soon it was noticed that the pulses coming from the pulsar were coming at varying frequency. It looked as if the bellows were being contracted and expanded in the hands of an invisible accordion player. This

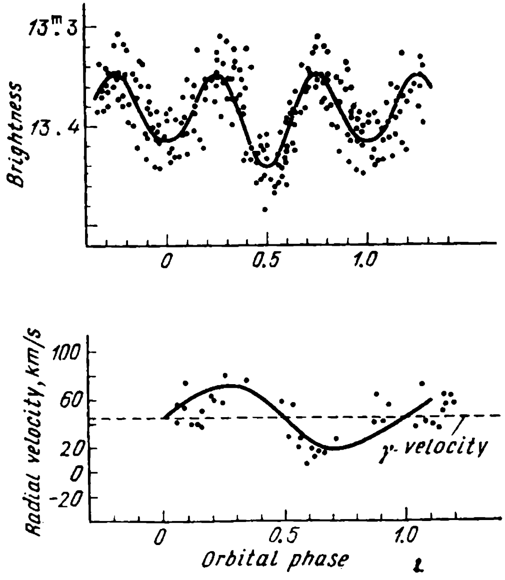
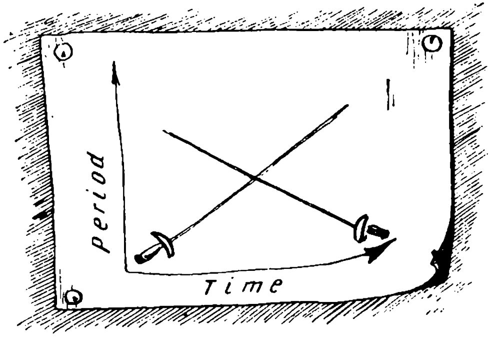


Fig. 53. Light and radial velocity curves of the optical component of Centaurus X-3

"melody", which had a period of 2.087 days, was soon explained. A pulsar's radiation is a periodic process and so subject to the Doppler effect. When the pulsar approaches us, the pulse period is reduced (the bellows are contracted) and when it recedes, the period becomes longer.

Thus the binary nature of the X-ray pulsar was proved. Moreover, every 2.087 days the X-rays disappeared. When the pul-



"*Relations*" *between radio and X-ray pulsars*

sar's X-ray light curve and radial velocity curve were compared, there was no doubt that the pulsar was periodically eclipsed by a second large star (Fig. 53).

X-ray equipment cannot yield accurate coordinates of the source, only a certain area (the error box) within which the source is located. Before long, a star whose light curve varied with a period of 2.096 days was found near the error box of Centaurus X-3. The minor difference could be explained by the inaccuracies in the determination of the optical light curve. Initially this

Table 2. X-ray pulsars

Name	Fluctuation period, s	Orbital period, days	Normal component	Characteristic time of acceleration, years	Luminosity, $L/L_\odot$
A 0538-66	0.069	16.66	Be		200000
SMC X-1	0.71	3.892	B0 I	1400	150000
Her X-1	1.24	1.7	HZ Her	340000	2500
H 0850-42	1.8				
4U 0115+63	3.61	24.31	B	30000	2500
V 0332+53	4.4	34	Be	200	
Cen X-3	4.84	2.087	O6 II-III	3400	12000
IE 2259+59	6.98	0.03			2000
4U 1627-67	7.68	0.0288	KZ Tra	5000	2000
2S 1553-54	9.26	30.07 (?)			
LMC X-4	13.5	1.408		> 1000	88 000

12*

2S 1417-62	17.6	> 15			⩽ 10000
OAO 1653-40	38.2			200	⩾ 100
A 0535+26	104	111 (?)	O9.7 IIe	1000	5000
GX 1+4	122	> 15	M6 IIIe	47	10000
4U 1230-61	191				
GX 304-1	272	135 (?)	B0-B5		500
Vela X-1	283	8.965	O-B	3000	350
4U 1145-61	292	187 (?)		> 1000	75
1E 1145.1-614	297	> 12	HE N 715	> 300	750
A 1118-41	405		Mira-type		1200
4U 1907+09	438	8.4	O-B		
4U 1538-52	529	3.73	B0 I	⪆ 500	1200
GX 301-2	696	41	A 977	⪆ 100	2500
X Per	835	580 (?)	O9	1400	2.5

explanation was accepted. As the number of observations grew, however, the difference between the X-ray and optical periods was neither eliminated nor reduced. Theorists would have had to burn a great deal of midnight oil had it not been for the

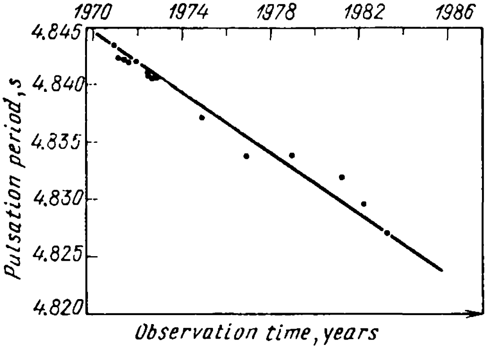


Fig. 54. A change in the period of the Centaurus X-3 pulsar

Polish astronomer Wojciech Krzeminski. In 1974, he found a star which, although located not far from the error box determined by Uhuru, had exactly the same period as the X-ray pulsar. The pulsar's neighbour turned out to be a blue supergiant with a mass of about $20M_\odot$. It was excellent proof of the theory: a massive binary, a blue supergiant with a strong stellar wind and a neutron star, the pulsar. All in all, about 20 X-ray pulsars, which for the most part are components of a binary, had been discovered (Table 2).

When the first X-ray pulsars were discovered, their discoverers were uncertain about what powered them. Many were impressed by radio pulsars. Soon, however, everything became clear. In contrast to radio pulsars, the periods of X-ray pulsars were not increasing, indeed, they were decreasing (Fig. 54). The only mechanism that could offer an adequate explanation to the luminosity of X-ray pulsars was accretion.

In the Stellar Wind

The optical light curve of Krzeminski's star (see Fig. 53) is a double wave with an amplitude of about 0.1^m. This is caused by the ellipsoidal effect and a weak eclipse. However, this small neutron star can hardly eclipse a supergiant. Since the neutron star itself does not actually radiate in the optical range, the system may not be eclipsing in visible light. Still there is a weak eclipse: the secondary minimum is deeper than the primary one. The normal star is probably eclipsed by a semitransparent accretion flow around the neutron star. It appeared possible to determine many of the binary's parameters using the visible and X-ray light curves and the radial velocity curves found from the spectral lines of the optical star and the change in the period of the pulsar. The binary is schematically shown in Fig. 55.

The optical star is very close in size to the Roche lobe but does not fill it. The same

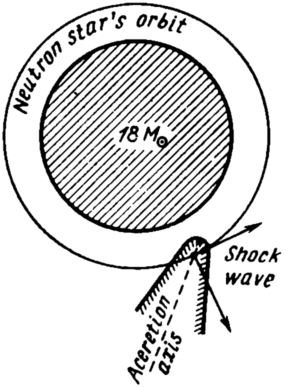
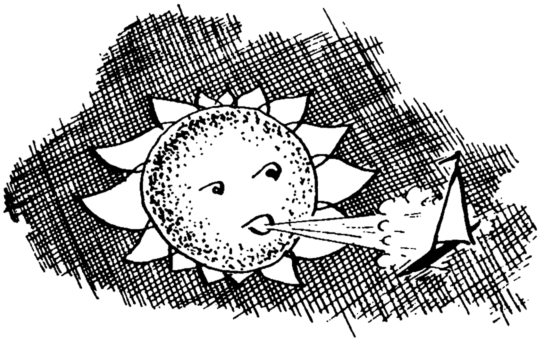


Fig. 55. The binary system of the Centaurus X-3 pulsar

thing occurs in some other pulsars. It seems that this is a direct indication that there is matter transfer through the inner Lagrangian point ("gravity wind"). However, this is hardly so.

Later astronomers discovered binary systems with bright X-ray pulsars in which optical stars were far from filling the Roche lobes. It is probable that in all these systems the main role is played by the stellar wind. A neutron star captures some matter from the stellar wind by its gravitational field (see Fig. 55). I have already shown that a neutron star needs only capture one thousandth or one ten thousandth of the matter flowing from a normal star to attain the



In the stellar wind

observed luminosity of pulsars, that is several thousands of times greater than the luminosity of the Sun. It is possible that in some cases the stellar wind is supplemented by a weak "gravity draught".

To see what then happens to the captured matter, we take an imaginary all-wavelength telescope and observe such a binary at a growing magnification. The size of a binary, i.e. the size of the neutron star's orbit within the system, is of the order of 10 million kilometres. The size of the normal star is of the same order. The size of the "sail" with which the neutron star captures the stellar wind is about 100 times smaller but is still hundreds of thousands of kilometres. From the side that is away from the wind a cone-shaped shock wave occurs. Shock waves appear when a fluid is strongly disturbed. Imagine a body moving in a gaseous medium. On the body-gas interface, the gas is slightly denser. This denser layer begins travelling throughout the gas with the velocity of sound. If the body moves at a supersonic velocity, it will go faster than the "perturbation", which is concentrated along the cone with a vertex near the body's surface, leaving them behind. Outside the cone the gas is at rest, for it does not yet "know" anything about the body. Inside the cone the gas is entrained by the body. In other words, on the cone's walls there occurs a sharp increase in the velocity and, consequently, in the pressure of the gas. By passing through the cone's wall, the gas is subjected to a kind of a blow. Since the neutron star is also moving, the wake turns along the vector of the difference in velocity between the neutron star and the stellar wind. The matter captured by the neutron star rushes towards it. Yet it does not fall directly onto the star. This is because of the angular momentum caused by the orbital motion. In some cases, the angular momentum is so substantial that an accretion disc appears around the neutron star. In other cases, the trajectory of the accreting matter is only a little twisted.

How an X-ray Pulsar Works

The accreting matter is actually a plasma, which conducts electricity very well. An ideal conductor can prevent external magnetic fields from penetrating. This ability

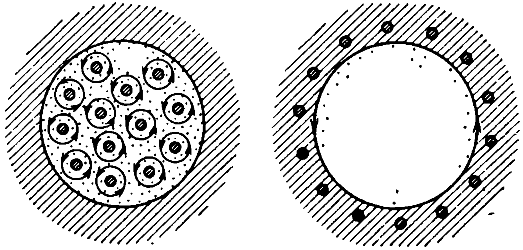


Fig. 56. A plasma's diamagnetism

is known as diamagnetism. A plasma's diamagnetism may be thought of in the following way. Suppose an external magnetic field has penetrated the plasma (Fig. 56). A plasma contains many free electrons. When acted upon by a Lorentz force, they all start rotating in the magnetic field in the same direction. Each electron creates its own small circular current. By adding with its neighbour, it cancels out. The surface current is the only one that remains. This current creates a magnetic field equal in magnitude and opposite in direction to the external field. The total field inside the plasma is, therefore, zero. The plasma as if pushed away the magnetic lines of force.

For the accreting plasma, the neutron star's magnetic field turns out to be "exter-

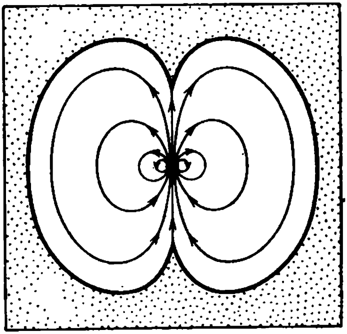


Fig. 57. A neutron star's magnetosphere for a case of radial accretion

nal" but staying inside it! As it falls onto the neutron star, the plasma compresses its magnetic field (Fig. 57) which, in turn, resists this compression. The pressure of the magnetic field rapidly increases as the distance to the neutron star decreases. At a distance of several thousands of kilometres, the magnetic field's pressure becomes equal to the neutron star's gravity. Here the neutron star's magnetosphere forms.

Now we shall see how matter penetrates to the neutron star's surface. It happens due to various hydromagnetic instabilities. The plasma cannot go through the lines of force but it can pull them apart and squeeze in. If there were no accretion disc, the plasma would accumulate on the neutron star's magnetosphere. The magnetic field is like an elastic "fluid" on which another "fluid", i.e. the plasma, lies in the gravity of the neutron star. As the plasma cools, it becomes thicker and "heavier". This is known as Rayleigh-Taylor instability and is what happens in a kettle or in a star's convective envelope. The heavy fluid (plasma) seeks to switch the roles with the magnetic field. The plasma pulls apart the lines of force and infiltrates into the neutron star's magnetosphere in the form of enormous drops which can be several hundreds of kilometres in diameter. Then the drops break into fragments. As a result, the electrons and ions start being affected by the magnetic field across which they cannot move. Thus they slide onto the neutron star's magnetic poles along the lines of force. The plasma eventually collides with the neutron star's hard surface at 100000 km/s and is heated to a temperature of several billions of kelvins. We needed a "hotter spot" and we got it! Here within a small spot of less than one square kilometre, half of the X-ray pulsar's total energy (for there are two poles) is released, with thousands of times the luminosity of the Sun.

If the neutron star is surrounded with a disc, the Rayleigh-Taylor instability does

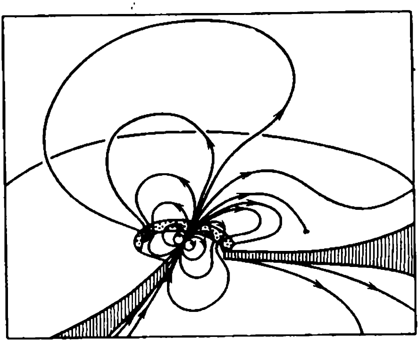


Fig. 58. A magnetic field's structure in the case of disc accretion

not "work" because matter rotating around a star is weightless. It is replaced, however, by the magnetohydrodynamic instability. As shown in Fig. 58, a thin accretion disc "constricts" the magnetic field, which is especially strong at the internal edge of the disc. The lines of force seek to straighten out, which requires a change of position between the plasma and the field. As a result of such instability, small blobs of the plasma enter the neutron star's magnetosphere to be broken into fractions and "frozen" into the field's lines of force. As if transported by rail the plasma rolls onto the neutron star's magnetic poles.

The surface of the disc is covered with waves due to what is known as the Kelvin-Helmholtz instability, something we come across every day. It ripples water, waves flags, and causes sails and curtains to flutter in the breeze. The origin of this instability is clear. Suppose we have two fluids, one static, the other flowing parallel to the flat interface between them (we shall assume that there is no gravity). The interface remains the same because all the forces are in equilibrium. Now we need only bend the interface a little. The pressure in the fluid at rest will not change; hence, the force acting from the static fluid on the interface will not change either. However, the pressure produced by the flowing fluid will decrease. The fluid flowing over the "hill" will be acted upon by a centrifugal force. Thus the "hill" grows, which means that the interface is unstable. The role of a flowing fluid in a river is played by the wind, and the height of waves is restricted by gravity.

The neutron star's rapidly rotating magnetic field acts as the "wind" on the surface of an accretion disc. The "waves" can rise to an altitude of several dozens of kilometres and plasma splashes get mixed up with the magnetic field. The resulting "seascape" is one no marine painter has ever seen or painted.

Most of the pulsar's energy is produced at the magnetic poles in a strong magnetic field of the order of 10^{12}-10^{13} G. Recall that the Earth's magnetic field is about 1 G. The radiation in such a strong magnetic field is anisotropic, and the neutron star illuminates the Universe with two X-ray beams, like a gigantic rotating lighthouse. Periodically, a beam strikes the Earth, and that's when we see the pulsar.

Why Neutron Stars?

Most X-ray pulsars have periods exceeding 100 s. What makes us believe these are neutron stars? No normal star could rotate at such a high rate because if it did the centrifugal forces would tear it into pieces no matter how large it is. Yet there are white dwarfs whose size (only several thousands of kilometres) allows them to rotate with periods up to several seconds.

Initially it was thought that X-ray radiation could only be generated by black holes and neutron stars. In the mid-1970s, however, astronomers discovered fluctuating radiation from white dwarfs in systems of the type AM Herculis, polars, which we shall discuss in the next chapter. It follows that neither the rotation rate nor the X-ray radiation is characteristic only of a neutron star.

Still it is possible to identify a neutron star unmistakably.

Here the fact that X-ray pulsars accelerate comes to rescue. It was, in fact, this property that "buried" the radio pulsar model of energy generation. I have pointed out more than once that the matter captured by an accreting star in a binary system possesses an angular momentum with respect to the system. The matter accelerates the star's rotation by falling onto it. That is what accelerates pulsars. The exact value of the accelerating impulse of the forces is dependent on many unknown parameters, e.g. the neutron star's magnetic field. There is, however, a restriction on the accelerating effect of falling matter, a restriction free of any supposition concerning minor details and which is dependent only on the star's rotation period and the accretion rate. Qualitatively, it is clear. If the matter had an infinitely large angular momentum, it would not fall onto the neutron star's surface and would not give up its momentum. The pulsar's period is known while the accretion rate may be obtained from its luminosity using formula (14). The smaller the star, the higher its acceleration for a given accelerating momentum. Neutron stars are hundreds of times smaller than white dwarfs. This means that the ultimate acceleration for neutron stars is much higher than that for white dwarfs.

The annual change in the pulsar's period is generally used as the measure of the pulsar's rotation acceleration. When the pulsars' annual acceleration was compared with the top limit established for neutron stars

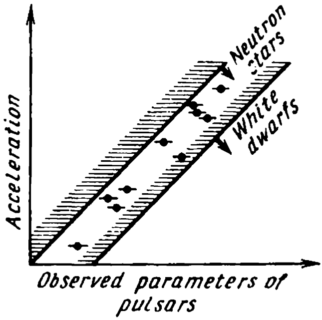


Fig. 59. The rotation acceleration of X-ray pulsars proves that they are neutron stars

and white dwarfs, it became evident that the pulsars (those whose acceleration has been measured) had been accelerating faster than white dwarfs were expected to do it (Fig. 59). Then it became clear that these were neutron stars.

"Discology"

The possibility of black holes is a significant result of Einstein's theory of relativity. Scientists are too impatient to wait until it is possible to create a black hole in the lab, so they are searching for natural ones. Where should we look for them? How do we tell a black hole from some other heavenly body? In most cases, it is easy to distinguish it from a normal star (not always! see Chap. 7). But how to distinguish it from a white dwarf or a neutron star? The latter is especially "unpleasant" in this sense. The size of a neutron star is only 2-3 gravitational radii. At these distances, a neutron star and a black hole do not differ in gravity at all. On the one hand, we know that a black hole has an event horizon, and everything that is behind it is lost for good. On the other hand, we know that for a distant observer on Earth a collapsing star never falls beneath the event horizon because of gravity-induced time dilation.

Is it at all possible to trace a black hole? The only characteristic feature of a black hole is its mass. We know that a neutron star cannot exceed the Oppenheimer-Volkoff limit, while a black hole's mass is unlimited. The problem is that the exact value of the Oppenheimer-Volkoff limit is so far unknown. *Advocati diaboli* argue that the limit may be $8M_{\odot}$, but it is more probable that it lies between $1.5M_{\odot}$ and $3M_{\odot}$.

In the mid-1960s, Soviet astrophysicists suggested that we should identify black holes by mass, which may only be estimated if the hole is a part of a binary system. If you run into a dark massive satellite, it is probably a black hole. This elimination method is very time- and effort-consuming.

Clearly, a black hole hunter has to know a more distinguishing feature. In 1972, Shakura published a paper in which he proved that the accretion disc around a black hole might be an X-ray source. He described the collision of matter with itself in the disc in the following way. The matter in the disc is engaged in three motions. The first one is a chaotic whirling known as turbulence. This occurs in rapid shifts of a fluid as happens, for example, in the turbulent wake of a motor-boat. In the disc, however, these motions are averaged. The second motion is the rotation of the matter as a whole around the attracting body according to Kepler's laws. A combination of these two motions initiates the third. Neighbouring rings rotate with different angular velocities and, owing to this, turbulent vortices in them collide and exchange momenta. As a result of this rubbing, the inner rings give their angular momenta to the outer ones. Kepler's second law is violated for the particles of the inner ring and they slowly move towards the disc's centre. A "Cassini division", however, does not appear because the centre-bound matter is replaced by another portion of matter, which gives its angular momentum to the ring that is farther from the centre. The result is a general radial motion of the matter to the centre accompanied by an outwardly directed transfer of angular momentum.

Such turbulent discs were first studied by the German physicist Karl von Weizsäcker in 1944, when he did research on the origin of the Solar System. In 1964, the Soviet astrophysicist Vitaly Gorbatsky examined turbulent disc-shaped envelopes in binaries exchanging mass. The English astrophysicist Donald Lynden-Bell first studied disc accretion on a gigantic black hole with a mass of about $10^6 M_{\odot}$.

This work was the birth of the new science on accretion discs (it is called in jest discology). For a long time, the turbulence was a stumbling block in discology. We did not know anything about the extent and nature of the turbulence, and it was impossible to make progress without this knowledge. Turbulence is, in fact, one of the most enigmatic phenomena in modern physics. Physicists have develcped general relativity theory, relativistic quantum theory, and now they are venturing toward a "grand unification" of all physical fields, but they have failed to answer fully why at a certain speed turbulence emerges in a fluid.

This poor understanding of turbulence hindered the development of discology. Probably, no progress would have been made if in 1972 Shakura had not found a way out by including our lack of knowledge about turbulence into one unknown parameter, i.e. some dimensionless number α. (The disc accretion model is, therefore, sometimes called the α-model.) In 1973, Shakura and Syunyaev used this simplifying assumption to solve the disc accretion equations, which stimulated the development of discology. Since then hundreds of papers on accretion discs have been published every year. Today, an attempt has even been made to treat the origin of the Solar System in the framework of the standard disc accretion theory.

What does an accretion disc around a black hole look like? Matter moves to the centre of the disc along a steep spiral path. As it approaches the black hole, both the rotation frequency (strictly according to Kepler's third law) and the difference in angular velocities of the neighbouring rings in the disc increase. The greater friction causes higher temperatures. At a distance of several dozens of gravitational radii, the temperature rises to one hundred million kelvins (see formula (12)). Nearly all the energy of the accretion disc is released in this zone (Fig. 60). When we rub our hands, muscular energy is released, while in the accretion disc the work is done by the black hole's gravity. The disc's inner boundary is located three (and not one) gravitational radii away. In the case of a neutron star, the disc is destroyed by the magnetic field. Now we shall see what destroys a black hole's disc so far away from it.

In fact, the disc is not destroyed at a distance of $3R_{gr}$. From this distance on, the matter falls freely, i.e. without friction, into the black hole. It turns out that circular orbits are not stable at distances less

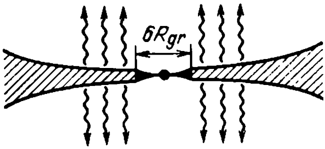


Fig. 60. Accretion disc around a black hole

than three gravitational radii. At shorter distances, the black hole's gravity grows much faster than $1/R^2$, and centrifugal force cannot withstand it. Therefore, when matter comes to within three gravitational radii, it is torn off from the disc and falls into the black hole without being heated and radiating anything.

The disc's inner parts are extremely unstable. The disc disintegrates into spots or separate hot areas which revolve around the black hole at a terrific rate. The characteristic period of revolution is one millisecond. An outsider observing these spots appear and disappear will get the impression that X-ray sources' periodicity is unsystematic and chaotic. This is exactly what was observed in Cygnus X-1.

Cygnus X-1 and Other Black Holes

Cygnus X-1, like X-ray pulsars, is one of the brightest X-ray sources in the Galaxy. Unlike an X-ray pulsar, however, Cygnus X-1 shows no periodic variation, instead, it fluctuates chaotically with extremely short periods (about 10^{-3} s). This variability was observed by American astrophysicists in the

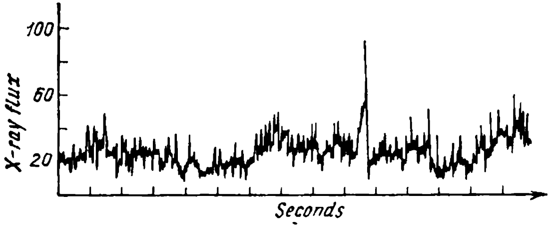
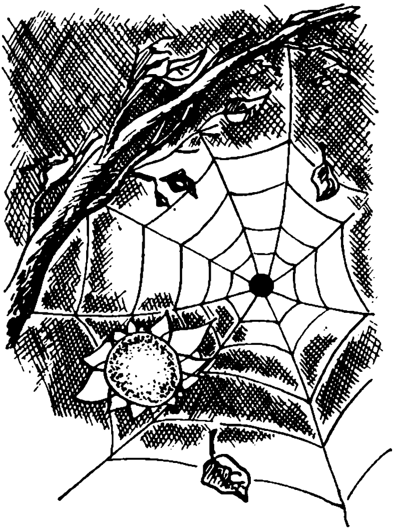


Fig. 61. A recording of the X-ray flux from Cygnus X-1

early 1970s (Fig. 61). It seemed evident that such a powerful X-ray source could only exist in a binary system, but it was impossible to identify the source as a binary due to the absence of X-ray eclipses. We were unfortunate because the angle of the system's inclination i is too small. Astronomers looking in the error box for some suitable optical star which could be the second component of the binary were attracted by a variable B0 supergiant, namely, V 1357 Cygni. They found out that the emission lines in its spectrum were "moving" with a period of 5.6 days. Soon the Soviet astronomer Viktor Lyuty discovered that V 1357 Cygni's light intensity



A binary with a black hole

fluctuated with the same period. This variable star's light curve is essentially a double wave and is given in Fig. 62. It resembles the curve of β Lyrae but differs in that in V 1357 Cygni both minima are of the same depth. This is a pure ellipsoidal effect. When the Soviet astronomers came to this conclusion, they surmised that the "ellipsoidality" could be explained if the second star's mass exceeded $5M_\odot$. You should bear in mind that the ellipsoidal effect makes it possible to estimate relative

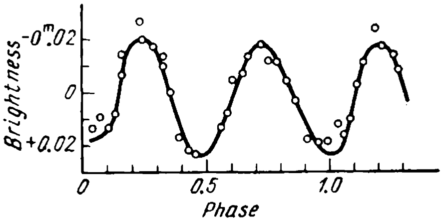


Fig. 62. The optical light curve of V 1357 Cygni

masses. The supergiant's mass, however, was found from its spectrum to be about $20M_\odot$.

The radial velocity curve was soon refined and it turned out that the mass function in that system is

$$\frac{M_x^3 \sin^3 i}{(M_0+M_x)^2} = 0.2M_\odot.$$

Substituting the supergiant's mass $M_0 = 20M_\odot$, we find that the minimum mass of the invisible companion (at an angle $i = 90°$) would be $5M_\odot$.* However, the

* It is not easy to solve such a transcendental equation, however, we can use the Newtonian method of successive approximations. We write the formula as $M_x = [0.2\,(M_0 + M_x)^2]^{1/3}$, then equate

angle is much smaller because there are no X-ray eclipses. Hence, the mass of the X-ray star is between $12M_{\odot}$ and $15M_{\odot}$.

Remember the story concerning the optical component of the X-ray pulsar Centaurus X-3? You will probably understand why astronomers are anxious to know whether the supergiant is simply projected onto Cygnus X-1 by chance. The situation is aggravated because Cygnus X-1 was for a long time the only worthy candidate for black hole status. Once in a while other candidates appeared but they either had regularly fluctuating X-ray radiation or their optical identification was wrong.

In 1983, astronomers discovered another probable black hole, LMC X-3. It was found in a neighbouring galaxy, namely, the Large Magellanic Cloud (LMC). It was the Uhuru satellite that recorded this X-ray source. The LMC X-3 source is extremely unstable, it "switches on" and "switches off". Like in Cygnus X-1, no X-ray eclipses were discovered. In 1983, American astronomers noticed radial velocity variations in the probable optical component, a B3 star, with a period of 1.7 days. The semi-

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M_x on the right-hand side to zero, find M_x on the left-hand side using a calculator, and substitute the quantity back on the right-hand side. By doing this repeatedly, you will get an answer to the accuracy of the number of decimal digits in the calculator.

amplitude of the radial velocity variations is about 235 km/s, which corresponds to a mass function of $2.3M_{\odot}$. If we take into account that the optical star mass is no less than $3M_{\odot}$, the invisible component's mass must be no less than $(3\text{-}4)M_{\odot}$, which already exceeds the probable Oppenheimer-Volkoff limit.

True, there may be mistakes in the optical identification. Although out of the ten candidate stars in the error box of the X-ray source, only the B3 star belongs to the Large Magellanic Cloud, there is no indication that the X-ray source itself belongs to the LMC. The research is continuing.

Back to the Scenario

In the early 1970s, the Soviet astrophysicists Alexander Tutukov and Lev Yungelson and a Dutch astrophysicist Edwin van den Heuvel working independently associated massive X-ray binaries with a special stage in the evolution of close binaries. Immediately after the formation of a relativistic star in a binary system, the normal star is still on the main sequence (Fig. 63*a*). The stellar wind of the normal star is still weak, and so the accretion rate onto the relativistic star is low and its X-ray radiation is insignificant. When the normal star leaves the main sequence to become a blue giant, the intensity of its stellar wind rises dramatically to about $10^{-6}M_{\odot}$ per year. This marks the birth of a powerful X-ray

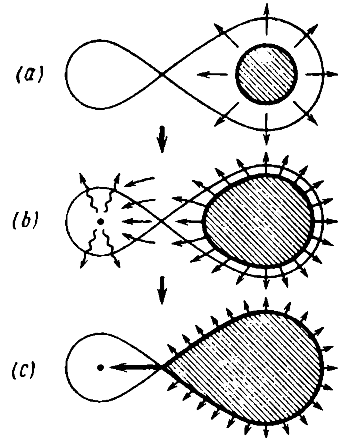

Fig. 63. Three stages in a binary's evolution after the first explosion

source with a luminosity many thousands of times that of the Sun (Fig. 63*b*).

This is consistent with observations of X-ray systems. Many components of X-ray sources are stars that have left the main sequence.

There exist, however, massive binaries in which the normal star is not a supergiant and still the X-ray source is very bright. These belong to the type of the pulsar

A 0535 + 26. (Here A stands for Ariel, the European satellite which discovered the X-ray source; then come the source's coordinates on the celestial sphere: $\alpha = 05^h35^m$ $\delta = +26°$.) Still the optical stars in these systems are extraordinary. They are all rapidly rotating Be stars.* The matter flow from these stars is very nonstationary and anisotropic. Inhomogeneous blobs of matter are torn off from the equator of the rapidly rotating star and captured by the relativistic star's gravity. These sources "work" only from time to time, which accounts for their name "transient".

Today astronomers have not yet found the place of these stars in the evolution of binaries. It is possible that Be stars acquire their rapid rotation as a result of the first mass exchange, during which the normal star receiving the matter is accelerated in the same way as an X-ray pulsar. Following collapse, the relativistic star "takes back" the matter it "lent" its partner. This may occur in the form of a stellar wind or a stream flowing from the equator.

However, there might be another solution to this problem and this is the second mass exchange through the inner Lagrangian point. Sooner or later, the second star must

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* Here Be stands for a B class star with emission lines.

fill its Roche lobe too (Fig. 63*c*). The matter transfer will occur on the thermal timescale (the matter will flow from the larger star to the smaller one). The rate of accretion onto the relativistic star will be (see formula (11))

$$\dot{M} = 3 \times 10^{-8} \left(\frac{M}{M_{\odot}}\right)^3 M_{\odot} \text{ per year.} \qquad (17)$$

If optical star's mass is $M = 20M_{\odot}$, the mass-flow rate will reach $10^{-4}M_{\odot}$ per year. If all this matter falls onto the relativistic star, then, according to formula (16), the star must become a source with a luminosity a billion times that of the Sun. I only want to say here that this is impossible, but I leave the details to the next chapter.

Now I would like to draw your attention to another factor. In a moderately massive binary the mass-flow rate is not high, and the relativistic star's luminosity will be less than 10000 that of the Sun. It follows that in such binaries an X-ray source flares up as soon as the normal star fills the Roche lobe and the second mass exchange begins. This is, probably, the only chance for a moderately massive system to become a bright X-ray source. A low mass star's stellar wind is thousands of times weaker than that of a supergiant. Strong accretion from the stellar wind as observed in massive X-ray system is only possible in systems with a red giant (giant by size).

Chapter 6

Dwarf Binary Stars

I have already said (see Chap. 3) that neutron stars have massive ancestors, and that stars with masses less than $10M_\odot$ turn into white dwarfs. Given this fact and given the conservative scenario (there is no loss of mass from the binary's during the first exchange), one might say that a low mass binary cannot evolve into a neutron star. In nature, however, there is no such rule, and neutron stars are often found in low mass binaries, as white dwarfs are.

Looking back at the late 1960s, the study of variable stars seemed a wonderland. Articles, books, and catalogues swarmed with the types of variables whose diversity terrified the theorist. There were novae, nova-like stars, recurrent novae, dwarf novae, flare stars, cataclysmic stars, eruptive stars, etc. Some stars were known simply as irregular variables, while some stars of the same type were often called different things. Any attempt at classification seemed hopeless.

Today we know why many stars behave strangely. We do not know everything but we know a lot.

Pussy, Pussy, Hercules X-1

The X-ray pulsar Hercules X-1 is one of the best-studied X-ray sources. Its radiation is periodic but has three different periods. This remarkable property has earned it the name a wonder clock. First, it pulsates with a period of 1.24 s. The X-ray light curve with this period is given in Fig. 64. Second, it has a period of 1.7 days. This light curve has one Π-shaped minimum.

Physiologists say that cats sleep for 18 hours a day. In other words, they are asleep for 75% of their lives. Hercules X-1 is like a cat. Every 35 days, Hercules is at "work" for 11 days, and for the next 24 days its X-rays do not hit the Earth at all. This is the third period.

The shortest period of 1.24 seconds is the period of the neutron star's rotation about its axis. The star's pulsation light curve in this case has two maxima.

The period of 1.7 days is, undoubtedly, the binary's orbital period. The short period of 1.24 s changes with the same period due to the Doppler effect. The 1.7-day change in the X-ray curve is the result of the eclipse of the X-ray source by normal star. It is interesting that the eclipse begins very abruptly. Recall that the duration of the decreasing part in a light curve is proportional to the size of the eclipsed star (see

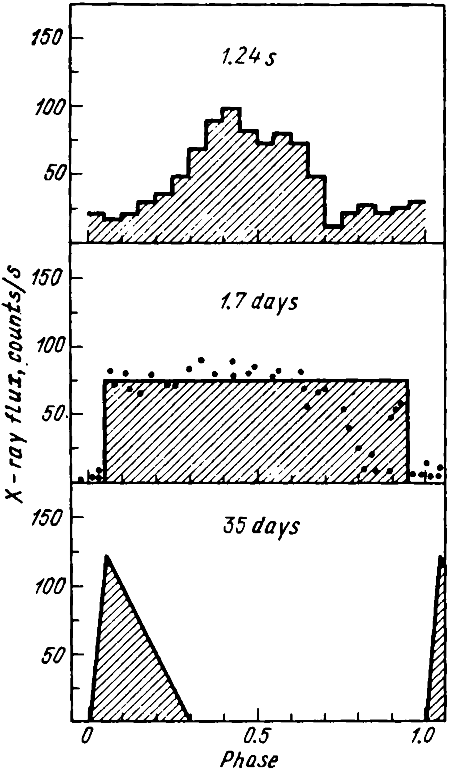


Fig. 64. Three periods of the X-radiation from Hercules X-1

Fig. 21). So here we deal with a star that is actually a point object.

The star that periodically obscures the X-ray pulsar was found by the Soviet astronomer Nikolai Kurochkin. Stars in X-ray detectors' error box included the variable star HZ Herculis of magnitude 12. Prior to the discovery of Hercules X-1 it had been listed as an irregular variable, which means that its light changed chaotically. Apparently, no astronomer had ever looked at its variability attentively. When the old plates stored at the P.K. Sternberg State Astronomical Institute were processed, it became clear that the light from HZ Herculis changes smoothly with the X-ray period of 1.7 days (Fig. 65). It was revealed that the visible light of HZ Herculis changes 13-fold (about 2.8^m), and during the X-ray eclipse, the system's optical brightness falls to a minimum. As in β Lyrae, the light curve has no flat parts but, in contrast to β Lyrae, it is not a double wave. It is rather a "single" wave with a maximum at phase 0.5. You probably remember that we have already come across this phenomenon in another classical star, namely, Algol, whose light curve tends to rise slightly by phase 0.5. Now there was no doubt that the whole light curve of HZ Herculis is the result of the reflection effect.

In 1967, Shklovsky emphasized that a very strong reflection effect must be inherent in X-ray binary systems. This phenomenon is basically the same as for normal stars,

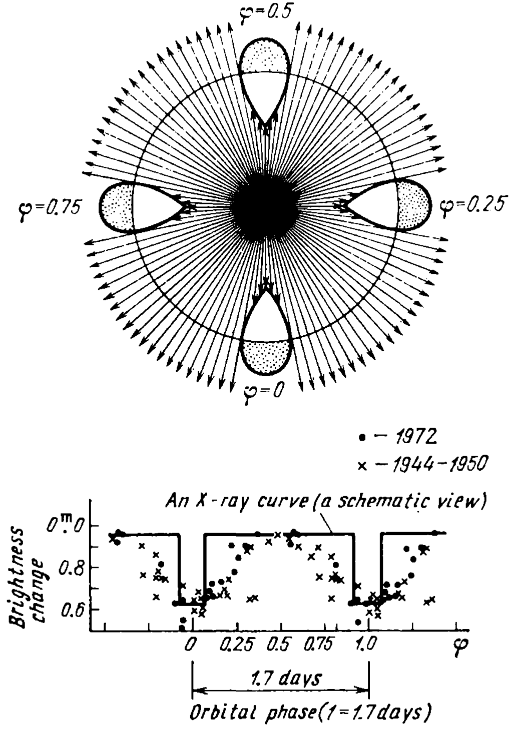


Fig. 65. A change in the brightness of HZ Herculis

the only difference being that in an X-ray binary the star is warmed up by intercepting the pulsar's hard X-radiation (Fig.

66). The X-ray luminosity of the pulsar Hercules X-1 is about 100 times greater than the total optical luminosity of the normal star HZ Herculis. Intercepting only part

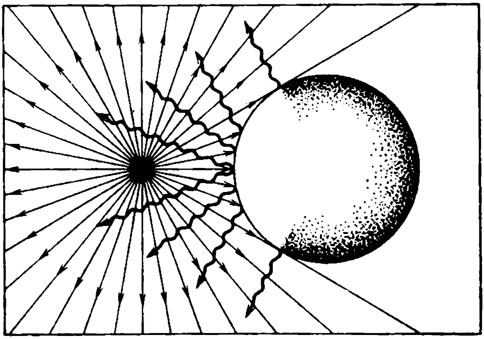
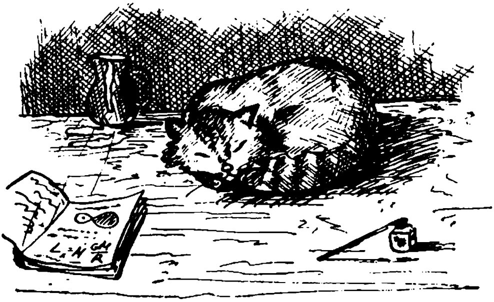


Fig. 66. A normal star's interception of X-radiation

of the X-ray radiation, the side of HZ Herculis which faces the pulsar becomes six times as bright as its opposite side.

The star's spectrum confirms this conclusion. At the minimum, HZ Herculis is a star of spectral class F and at the maximum of class A0. According to the mass-luminosity relation, the optical star's mass is (2-2.5) $M_{\odot}$. The duration of the X-ray eclipse allows us to estimate the size of HZ Herculis, which is very close to the Roche lobe. This system is, probably, undergoing the second mass exchange: the normal star has filled its Roche lobe and matter is flowing through the inner Lagrangian point in the form of a gravity wind. The gas stream forms an accretion disc around the neutron star. An observer near the accretion disc would see the following sight. At the "horizon", there is the optical component, i.e. the star HZ Herculis and a stream of gas flowing from it. As the disc approaches the neutron star, magnetic forces start bending its surface, which is covered with "ripple" due to Kelvin-Helmholtz instability. Eventually, the disc is broken up by the magnetic forces at a distance of several thousands of kilometres. The matter is then "frozen" into the magnetic field and flows down onto the neutron star's magnetic poles, which produce two X-ray beams.

It is not yet clear, though, why Hercules X-1 is as sleepy as a cat. By the way, the fact that for us on Earth the radiation disappears for 24 days every 35 days does not indicate that the pulsar takes a 24-day holiday. Even when the pulsar is "off", its optical light curve remains the same, that is, the reflection effect does not disappear. Something seems to be obscuring the neutron star from us, but this something cannot screen all the X-radiation falling onto its companion, HZ Herculis. The accretion disc around the neutron star, probably, serves as a screen. Since the binary's orbital plane lies actually in the line of sight, the disc which wobbles slightly with respect to this plane blocks the pulsar's radiation from us for



Hercules X-1

some time. The accretion disc's shadow on the companion star is not large and has virtually no impact on the reflection effect.

The HZ Herculis—Hercules X-1 system is a low mass binary. You may ask how a neutron star, whose ancestor must have had a mass of more than $10M_{\odot}$, could have evolved in such a low mass system. A probable answer was offered by van den Heuvel in 1977 (Fig. 67). In a nutshell, he suggested that the first mass exchange was not conservative.

The reason for the system's great loss of mass lies in the large initial difference between the star masses. Note that the outflow of matter from a more massive component to a less massive one occurs on a thermal timescale. Because of the large difference in mass, the less massive star's thermal time is tens and hundreds of times larger than that of its more massive companion. The

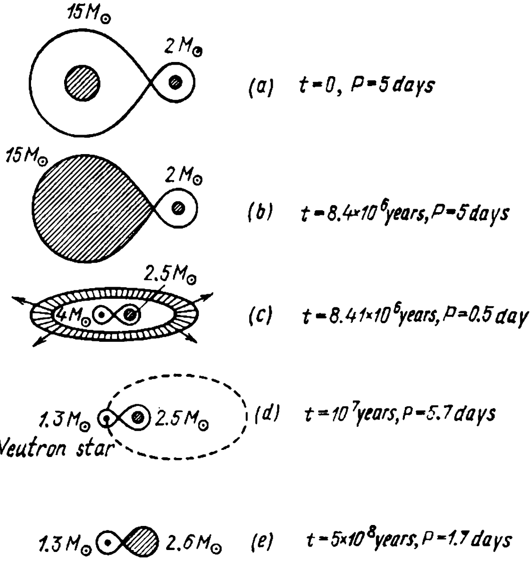


Fig. 67. The evolution scenario in which a massive binary evolves to become a system like HZ Herculis—Hercules X-1

accreting matter does not have enough time to attain thermal equilibrium and settle on the star. Let us assume that such a rapid mass transfer results in the formation of a common envelope with mass flowing from the binary. If so, what is happening is not a mass exchange but a total loss of mass from the system. The low mass star remains almost unchanged, while its more massive partner collapses into a neutron star. The system's total mass does not exceed $(3\text{-}4)M_{\odot}$. When the envelope is pushed away, the binary loses both material and angular momentum, i.e. the stars move closer to each other.

Finally, due to its nuclear evolution, the less massive optical component will fill its Roche lobe and thus initiate the second exchange, in which a bright X-ray pulsar will flare. According to van den Heuvel, this is how a system such as HZ Herculis—Hercules X-1 appears.

Today we know of several systems like HZ Herculis. They are not very numerous because when first formed the masses of a binary's stars are about the same. It is very seldom that a binary is formed whose components differ very greatly in mass. Van den Heuvel's scenario shows how a neutron star can be "smuggled" into a low mass binary system, while a binary's legitimate child should have been a white dwarf.

Novae and Recurrent Novae

The outburst of a nova is as impressive as a supernova explosion. A bright star may be visible with the naked eye where sever-

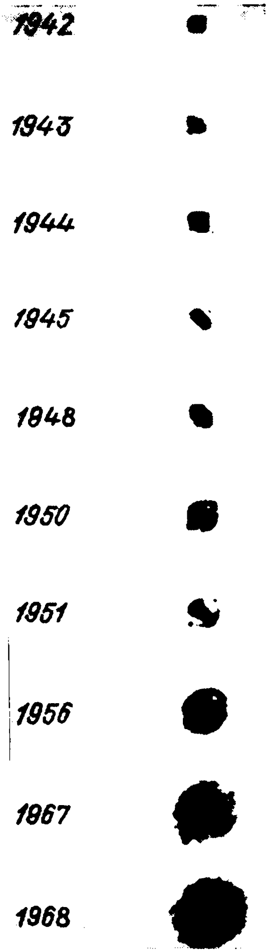


Fig. 68. The envelope ejected by a nova explosion

al days before there was nothing. This is exciting for someone used to an invariable celestial sphere occasionally crossed by artificial satellites. This interesting physical phenomenon has always fascinated stargazers and inspired poets. When the nova V 1500 Cygni began shining in the sky, astronomers looked through old plates to discover that prior to the nova explosion there had been a star 10-12 magnitudes weaker than the nova. For some reason, the star had suddenly increased its luminosity by tens of thousands of times. Note that the explosion of a supernova increases its energy output as much as a billionfold. Novae are less spectacular, but seem as bright as supernovae because they are much closer to us.

A nova reaches peak intensity and then slowly fades to its original brightness over several months. Some years pass, and in the place of the explosion a vague spot appears, which indicates that the nova's explosion was accompanied by the ejection of matter into space (Fig. 68).

Long ago astronomers noticed that there were stars which exploded more than once. True, their explosions were weaker than true novae. Table 3 is taken from a book by the well-known Soviet expert in variable stars Vladimir Tsesevich and it lists the characteristics of nova explosions. The explosions of recurrent novae are much weak-

Table 3. Novae

Name	Year of discovery	Magnitude at a maximum	Orbital period, days	Luminosity before and after the explosion, $L/L_{\odot}$	
GK Persei	1901	0.2	0.685	1.2	251000
DN Geminorum	1912	3.6	?	3.3	100000
V 603 Aquilae	1918	−1.1	0.138	8.3	480000
V 476 Cygni	1920	2.0	?	1.6	690000
RR Pictoris	1925	1.2	0.145	1.3	91200
DQ Herculis	1934	1.3	0.194	0.06	17400
CP Lacertae	1936	2.1	?	2.8	525000
CP Puppis	1942	0.5	?	0.06	440000
V 1500 Cygni	1975	1.8	0.14		250000

er than those of the novae and occur decades apart.

DQ Herculis (Nova Herculis 1934) is one of the best-studied novae and it exploded in 1934. At its peak intensity it was one of the brightest stars in the northern sky. Old plates showed a star of magnitude 15 where the nova appeared. After its peak intensity the star faded, then suddenly increased its brightness for 100 days and finally faded again to magnitude 15 (Fig. 69).

In 1954, the American astronomer Merle Walker made a discovery which shed more light on the nature of novae. A thorough study of DQ Herculis showed that the star fluctuated in brightness with a period of 4 h 38 min (0.194 day). Its light curve proved that DQ Herculis is an eclipsing variable star (Fig. 70) and its spectrum contained bright emission lines of hydrogen and helium. Its light curve and radial velocity curve indicated to astronomers that

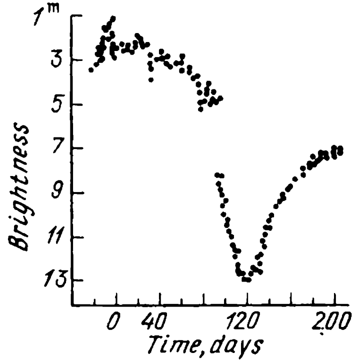


Fig. 69. A change in brightness of DQ Herculis

the binary's total mass is smaller than the mass of the Sun! This is a low mass system composed of a cold red dwarf and a compact hot star. The radiation lines were "moving" in the spectrum with the orbital period but did not coincide in phase with any star. This proved that there were large gaseous streams in the system.

In 1956, Walker made another important discovery. It turned out that the system's light "oscillated" by several percent with a definite periodicity (Fig. 71), repeating

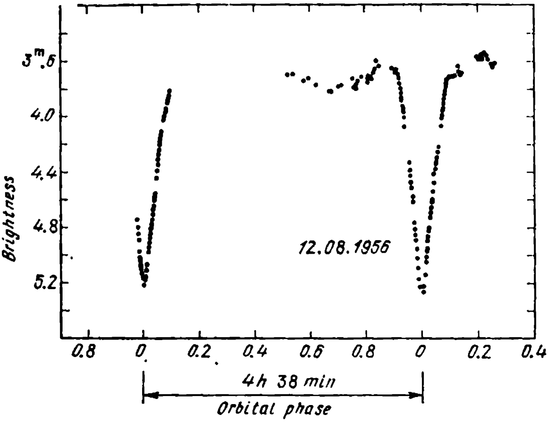


Fig. 70. The light curve of DQ Herculis

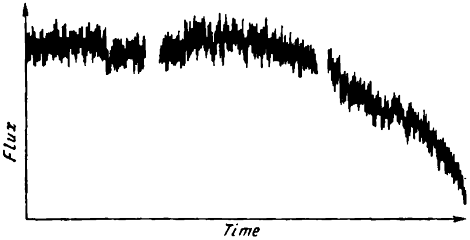


Fig. 71. The oscillation in the light from DQ Herculis with a period of 71 s discovered by Walker in 1956 (before the discovery of radio pulsars)

itself every 71 s. Thus the first pulsar had been discovered. It was found for a white dwarf and not for a neutron star!

In order to rotate so fast, the star had to be either a white dwarf or a neutron star. The star could not be neutron for a number of reasons. The pulsar's mass in this system is much smaller than the Chandrasekhar limit. Yet while I say that the neutron star hypothesis is unlikely it is not impossible. In 1937, Landau proved that the neutron star's smallest possible mass is much less than the Chandrasekhar limit. True, it is energetically more favourable for a low mass star to be a white dwarf than a neutron star, because the latter needs "looking after" and has to be "prepared" under special conditions. However, a whole set of observational data indicates that the star is a white dwarf.

The gaseous streams in a binary occur because the red dwarf star fills its Roche lobe. What is happening here is very much like what we have seen in the HZ Herculis system, the only difference being that the neutron star is replaced by a white dwarf.

A white dwarf is about 1000 times the size of a neutron star, which makes the accretion mechanism 1000 times less effective. When accreting onto a white dwarf, only 0.01% of the rest mass, not 10%, is released, i.e. less than in fusion reactions. Having no other energy source, the white dwarf has to rely on accretion. By the way, these figures show that for the same accretion rate a neutron star must be 1000 times brighter than a white dwarf. This agrees with what we observe: the luminosity of systems of the DQ Herculis type is several times the luminosity of the Sun or, in other words. about 1000 times weaker than that of the HZ Herculis--Hercules X-1 and similar systems.

Now let us see what causes a nova or a recurrent nova to explode. You know that white dwarfs are formed from not very massive stars and that the maximum temperature at the star's centre depends on the star's mass. There is a moment when there are no more elements at the star's centre to support fusion at a given temperature and density. The isothermal nucleus contracts to become a white dwarf in whose interior nuclear reactions are impossible.

Nothing happens to a single white dwarf other than it gradually cools. Things are different when it has a partner. The companion star flows onto the white dwarf and adds fresh fuel ready for burning. On the other hand, the accreting material becomes hotter because it hits the white dwarf's surface. For fusion to begin, it is necessary that the density and temperature of the matter exceed certain critical values. The temperature in the inflowed layer varies with the inflow of energy. As a first approximation, we assume that the energy inflow is constant and, therefore, the temperature is constant too. As for the density, it grows slowly with increasing the layer's mass. When the layer reaches a critical mass, it explodes. Matter is ejected into space at a very high speed. As the area grows, the luminosity increases, and we observe a nova explosion.

A nova differs from a recurrent nova, probably, in that helium explodes in the former and hydrogen explodes in the latter. The burning of helium requires a higher density and, consequently, more time to explode. The explosion, however, is far more powerful due to the greater amount of matter involved.

The idea of nuclear burning in a thin layer on a white dwarf was discussed by scientists as far back as the 1940s, but it was in the last decade that the relationship between this phenomenon and accretion in close binaries was established. Roughly, we can estimate how often novae explode because it is assumed that they are also recurrent.

An analysis of nova explosions shows that every explosion ejects $M_{\text{total}} = 10^{-5} M_{\odot}$. If we assume that the accretion rate is standard, i.e. $\dot{M} = 10^{-10} M_{\odot}$ per year, then the mass ejected in an explosion will be replaced in about $t \simeq M/\dot{M} = 10^{5}$ years. On the other hand, hydrogen explodes under milder conditions, i.e. more frequently.

Clearly, these are only estimates and our understanding of what is happening in reality is still vague. For instance, white dwarfs have strong magnetic fields. We know that DQ Herculis is a pulsar and its magnetic field (about 10^5-10^6 G) is strong enough to make matter fall onto the poles. The area on which the matter falls, as well as the temperature, depend on the magnetic field strength and the accretion rate. The whole picture becomes more complicated because the material outflowing in different binaries has different chemical compositions, and dwarfs are not identical either. This is where the apparent diversity in novae and recurrent novae comes from. The behaviour between explosions is determined by the nature of the accretion, which is also extremely varied.

U Geminorum Stars

In military terms, we could say that novae and recurrent novae are like heavy artillery, while explosions of U Geminorum stars are like machinegun bursts. The explosions are only several months apart and there is no fixed periodicity, although there is definitely repetition. Table 4 lists the characteristics of some U Geminorum stars. All in all, we know of over 300 such stars.

Table 4. U Geminorum Stars

Name	Cycle duration, days	Orbital period, days
U Geminorum	103	0.177
SS Aurigae	57	0.180
EX Hydrae	558	0.068
SS Cygni	50	0.276
RU Pegasi	68	0.371
Z Chamaeleontis	104	0.0745

The Polish astronomer Krzeminski (who correctly identified the X-ray pulsar Centaurus X-3) calculated that the U Geminorum star's light between explosions changed with a period of 4 h 14 min (0.177 day). The light curve is unstable (Fig. 72) and changes shape. However, it reproduces its typical shape partially or completely from one cycle to another.

We have not yet come across such an extraordinary light curve. We can "straighten it out" using the radial velocity curve. At the primary minimum ($\varphi = 0.5$), the radial velocity is zero, which means that the lines are associated with the eclipse of a hot and bright area. The light changes are sketched in Fig. 73.

The light curve is peculiar because the minimum is not symmetric. At first, the star gradually enters the minimum. At a certain phase, the light curve abruptly falls, indicating a rapid entry into the eclipse. You get the impression that the bright area is first obscured by one body and then by some other. It is interesting that the shape

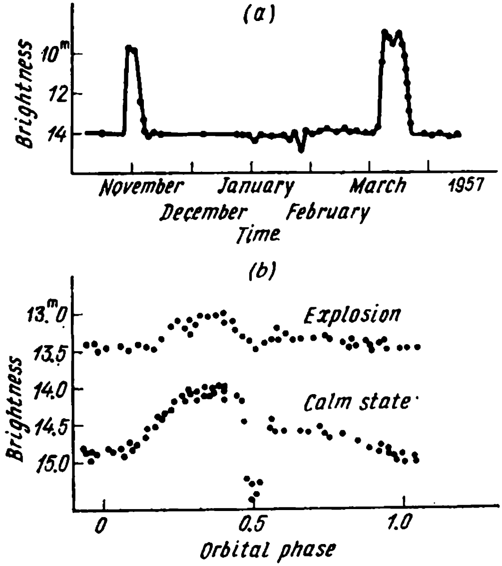


Fig. 72. A change in brightness of the U Geminorum star: (*a*) long-term change; (*b*) orbital change

of the eclipse's initial stage depends on the wavelength of observation. Only one explanation seems possible, that is, the start of the minimum (section *1-2*) is an eclipse by a semitransparent body, the next stage

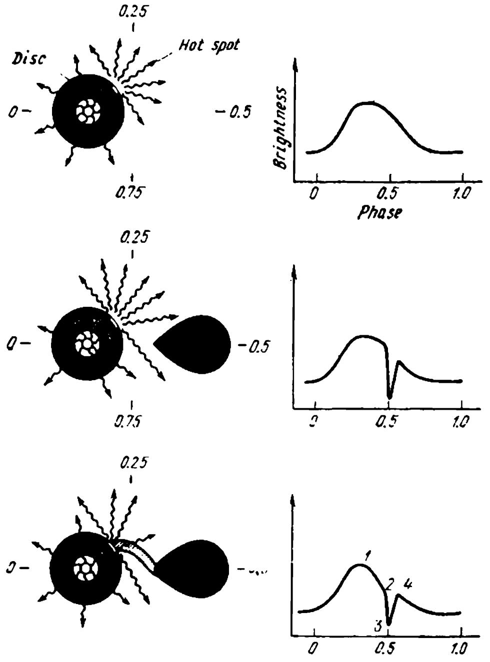


Fig. 73. A synthesis of the light curve of a U Geminorum star. Top, the light curve of the hot spot on the disc. For half a period, the spot is seen from phase 0.12 to 0.62, while for the remainder of the time it is obscured by the accretion disc. In the middle, you see the light curve change caused by the eclipse by the companion star; a minimum appears at phase 0.5. Finally, at the bottom, an eclipse by the semitransparent gas stream is taken into account; it reduces the brightness (section *1-2*)

(sections *2-3*, *3-4*) is an eclipse by an opaque body (see Fig. 73).

This can easily be explained in the following way. Imagine a system of two stars in which one star is surrounded by a disc. On the disc there is a bright hot spot, slightly to one side of the line connecting the stars. The spot is so bright that it actually accounts for the brightness of the entire system. If we had only this spot and the disc, the light curve would be bell-shaped with a top to the left of phase 0.5. At the maximum, we would see the whole spot (front view). The spot, however, is a little away from the line connecting the stars; therefore, the phase is also a little shifted. Now we shall add the companion star. Now the eclipse will appear exactly at phase 0.5. This picture needs a final touch. Let the dark star release a flow of semitransparent gas toward the disc. This will cause a sharp break (section *1-2*). First the spot is obscured by the flow, then by the star. This explains why the minimum is not symmetric.

The spectra analysis shows that U Geminorum stars contain a red dwarf whose mass is several tenths of the mass of the Sun, and a white dwarf surrounded by the accretion disc. For some unknown reason, the accretion disc and the white dwarf, unlike DQ Herculis stars, emit almost nothing.

The origin of the bright spot is fairly clear. The gas flowing from the red dwarf, which fills its Roche lobe, does not "wind" around the disc, but hits it at an angle. The angle of attack may be quite large, and the result may be a shock wave at the collision site, which is a narrow area where the speed of the gas decreases and its temperature increases dramatically. The stream's kinetic energy is converted into potential energy.

It is easy to estimate the luminosity of such a spot. If the speed of the stream relative to the disc is v, the kinetic energy of the gas unit mass in the stream is $v^2/2$. On impact with the disc, nearly all the energy turns into heat and light. Therefore, each kilogram of gas in the spot radiates approximately $v^2/2$ J. The stream carries $\dot{M}$ kilograms per second, so the spot's total luminosity is

$$L_{\text{spot}} = \dot{M}\frac{v^2}{2}. \tag{18}$$

In such dwarf systems, the matter in the stream may be moving at several hundreds of kilometres per second, and the flow rate may be 10^{-8}-$10^{-7} M_\odot$ per year. The spot's luminosity would be comparable with that of the Sun. The stars themselves in these systems glow tens and hundreds of times more feebly, so it is small wonder that the spot outshines the stars.

We are not certain why a white dwarf surrounded by an accretion disc doesn't radiate any energy between explosions. It could be that between the explosions there is no accretion because in the discs of such systems there is no friction and they gradually increase in mass without accreting. When the disc density reaches a certain value, turbulence abruptly increases, and the accretion on the white dwarf begins, which we describe as an explosion. The disc "flows" onto the white dwarf, friction disappears again, and the whole process is repeated. If so, why? Today this question is unanswered.

Can we suggest that the absence of accretion between explosions is explained by the propeller effect? If the white dwarf rotates rapidly, its magnetic field will impede the fall of the matter on its surface. In this case, the matter will accumulate in the disc, the pressure in it will rise, and the disc's inner boundary will move slowly toward the white dwarf. The speed of the magnetic field's lines of force will decrease as they move closer to the white dwarf because the lines of force rotate like a rigid body together with the white dwarf. At some moment, the propeller effect disappears and the matter falls onto the white dwarf's surface. The result is an explosion. Then everything repeats again.

Indeed, calculations show that a white

dwarf in such a system must rotate at a very high rate, i.e. with a period from several seconds to several hundreds of seconds.

Generally speaking, U Geminorum systems have another kind of explosion, which have a much greater output but are much shorter. These may be caused by a thermonuclear explosion of the matter rich in hydrogen and flowing onto the white dwarf's surface.

In one star in this category, namely, SS Cygni, astronomers have recorded an outburst of X-ray radiation pulsating with a period of 8 s. This is exactly the period the white dwarf should have in such a system.

Polars

Another class of dwarf binaries called polars was discovered in the mid-1970s. The first polar to be found was AM Herculis, the third remarkable star from the constellation Hercules after HZ and DQ.

This star has taught astronomers many lessons. The main one was that an accreting white dwarf might produce a hard X-radiation. True, American astrophysicists first noticed in 1967 that the accretion on white dwarfs might be accompanied by a considerable X-radiation, but it was taken for granted for a long time that white dwarfs could not radiate X-rays. This belief was refuted in 1976 when the American satellite SAS-3 (Small Astronomical Satellite) discovered oscillating X-ray radiation with a period of 0.129 day (about three hours) emanating from AM Herculis. Optical light from this star also varies between the 12th and 13th magnitudes with the same period.

Emission lines in the star's spectrum showed evidence of strong gaseous streams, and the radial velocity's semiamplitude was 240 km/s. Such a high speed as due to the system's small size and not its great mass. And the period is only 3 hours!

I shall give you an example illustrating the situation in this system. If we were to put an artificial probe into low solar orbit, it would go around the Sun in 2 h 40 min. The mass of the stars in AM Herculis is less than that of the Sun, and the binary's size turns out to be less than the Sun's radius.

The most surprising thing about this system was that the visible light emitted by AM Herculis was very polarized. This is why the AM Herculis stars are known as polars.

I would like to remind you that what we call visible light is a set of electromagnetic waves. Each wave is composed of crossed oscillating magnetic and electric fields (Fig. 74). In each wave, the electric (or magnetic) vector's oscillation plane is fixed and does not change. The combination of waves in which the oscillation planes of the electric vectors do not coincide is called unpolarized light. In contrast to this, light is polarized if there is a plane in which most waves oscillate. Ordinary substances, like glass, allow light to travel

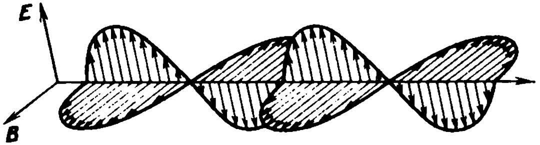


Fig. 74. In an electromagnetic wave, the electric vector **E** oscillates in a plane perpendicular to the oscillation plane of the magnetic induction vector **B**

freely irrespective of its polarization. In nature, however, there are light-polarizing materials (polarizers) which only allow light to pass if its polarization plane is oriented in a certain way. This is because the crystals which make up polarizers have some preferred directions (faces).

To illustrate how a polarizer works and what polarization is, I shall give you an example from everyday life. If you want to enter the Moscow underground, you must do at least two things: take a five-kopeck coin out of your pocket and align it with a slot in the coin changer. Before you enter the underground, the coins in your pocket are unpolarized, i.e. they are oriented at random. The coin changer functions as a polarizer polarizing your coins as soon as you enter the underground.

This is a trivial example but it shows us how to determine whether a star's light is polarized. We put a polarizer at a telescope's focus. It allows the light to pass through only if the waves' plane coincides with the direction of the "slot", which blocks all other waves. By rotating the "slot" about the telescope's axis, we see the star's light change. If there is no change, the light is not polarized. In most cases, the light given off by stars is unpolarized.

Things are different with AM Herculis. If we rotate the polarizer, we see its light change by more than 10%. Note that the polarization also changes with the same period of three hours (Fig. 75).

The star's light curve and spectrum indicate that the main contribution to its luminosity is made by a white dwarf while the second star, a red dwarf, is, in fact, invisible. Let us see why the light emitted by the white dwarf is so strongly polarized. The reason is that it is not the ordinary radiation emitted by a plasma but the radiation of electrons moving in a strong magnetic field. This radiation is known as a cyclotron radiation.* It is generated at the

* So called because it was first recorded in cyclotrons, i.e. in charged particle accelerators.

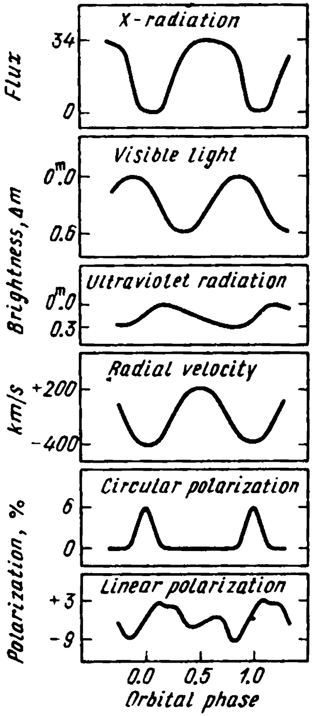


Fig. 75. Variations of different characteristics of radiation from AM Herculis with orbital phase

surface of a white dwarf with a very strong magnetic field, say, of the order of 10^8 G, which is about 100 times stronger than that of the white dwarf in the DQ Herculis system. The material accreted by the white dwarf gets heated by hitting the surface and part of that energy is emitted in the form of X-radiation, i.e. following usual mechanism when electrons pass near ions (free-free radiation). The rest of the energy is emitted as the electrons revolve in the white dwarf's strong magnetic field. Cyclotron radiation has an optical wavelength, i.e. it is a visible light.

The way the mass flows in this system is also unusual. Soviet astrophysicists discovered that if the white dwarf truly possesses such a strong magnetic field then the latter starts governing the motion of matter as soon as the matter leaves the red dwarf. In fact, the red dwarf lies within the white dwarf's magnetosphere (Fig. 76).

The fact that the X-radiation and the visible light fluctuate with the orbital period indicates that the white dwarf always shows the same face to the red dwarf (like the Moon faces the Earth). This is hardly surprising since it has been calculated that the strong magnetic fields tie the stars into such a close system that the stars quickly synchronize their rotations. Now we know of about ten such systems.

A high degree of polarization is not the only peculiarity of these systems. They also have very characteristic visible light fluctuations. Every few months the system fades tenfold or more.

A skilled interpreter of a system's light can determine whether it is a polar or not. Soon after the discovery of AM Herculis, the young Soviet astronomer Sergei Shuga-

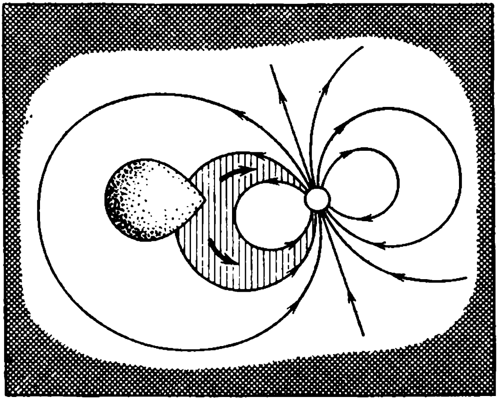


Fig. 76. Matter flow in AM Herculis binaries

rov nominated another candidate for the polar club, namely, the star AN Ursae Majoris. His only evidence was variations in the star's brightness. Several months passed, and X-radiation from this star was discovered.

Those Supernovae That Are So Much Alike

Following Baade and Zwicky, we could associate the explosions of all supernovae with the birth of neutron stars and, possibly, black holes. Stellar evolution theory says that neutron stars' ancestors are massive stars.

Long ago astronomers noticed that, paradoxical as it might seem, supernovae often erupt in elliptical galaxies which have no massive stars at all. We can solve this problem by assuming that the exploding stars are binaries. Supernovae which erupt in elliptical galaxies are very much alike and in this they are peculiar. They even constitute a separate class known as type I supernovae. It is typical that after the maximum they fade very quickly (Fig. 77). In several weeks, the star becomes 6-8 times fainter, then comes a period of a slow linear decline in brightness which lasts for several hundred days.

There are also type II supernovae. Their maximum is followed by a flat part of the light curve which lasts for several months and ends with a rapid decline (see Fig. 77). Supernovae of this type are more varied but all erupt in spiral galaxies, as a rule, in the spiral arms, densely populated by massive short-lived stars. Type II supernovae occur as a result of the collapse of massive stars.

Type I supernovae also explode in spiral galaxies, but they do not tend to concentrate

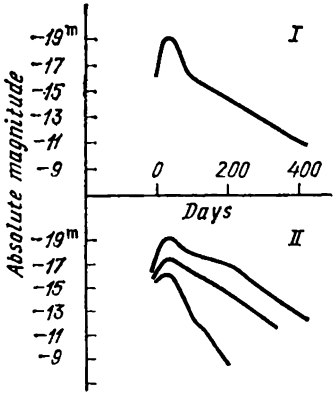


Fig. 77. Typical light curves of type I and II supernovae

in the spiral arms. Statistically, type I stars are somehow connected with low mass stars.

In 1963, the French astrophysicist Evry Schatzman noticed that white dwarfs in low mass systems may collapse because of the accretion of matter flowing from the companion star onto them. A white dwarf whose mass is initially below the Chandrasekhar limit grows to the limit, then loses stability, and starts collapsing. Let us see how this happens. Calculations indicate that the contraction of a white dwarf composed of helium or carbon is followed by a rapid rise of temperature at the centre. The temperature is so high that the result is a nuclear explosion and the complete disintegration of the white dwarf. This explains why the explosions of type I supernovae are so much alike; it is because the exploding stars have the same mass equal to the Chandrasekhar limit.

If this is true, the light curve of a type I supernova is very elegantly explained. The nuclear burning of a white dwarf produces a large quantity of the nickel isotope ^{56}Ni. This isotope is radioactive and it decays spontaneously into cobalt ^{56}Co, which, in turn, decays into iron ^{56}Fe:

$$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe.$$

Nickel's half-life (the time in which the number of radioactive atoms is halved) is 6.1 days, while that of cobalt is 77 days. The energy from the cobalt decay is taken away by electrons which later reemit this energy thus ensuring the luminosity of the supernova's remnants which are ejected into space. The observed light curve is the result of the nickel and cobalt decay.

At the same time, white dwarfs composed of heavier elements like carbon, oxygen, and magnesium (see Fig. 39) are not completely destroyed and give birth to neutron stars.

It is clear that Schatzman's hypothesis is another way of "smuggling" neutron stars into low mass systems. Like van den Heuvel's nonconservative scenario, it also implies the formation of low mass X-ray systems.

I wonder if novae, nova-like systems, U Geminorum systems, and polars are all stages to a supernova explosion. These are systems in which there is accretion onto white dwarfs. I don't think we should rush to any conclusion but there is evidence that at least some of these systems yield supernovae.

X-ray Bursters

In 1975, the American astrophysicist George Grindlay and his colleagues discovered a totally new type of X-ray source. A mysterious source was sending out short (100 s) bursts of soft X-radiation every few hours (Fig. 78). (This is where the word "burster" comes from.)

Between bursts the radiation did not disappear completely, but it had a far harder spectrum. Astronomers hunting for the optical "double" found that the X-ray source was located in the direction of a globular cluster.

A globular cluster is a special kind of stellar association with a very high density of stars. On average, a globular cluster about one light-year across contains up to a

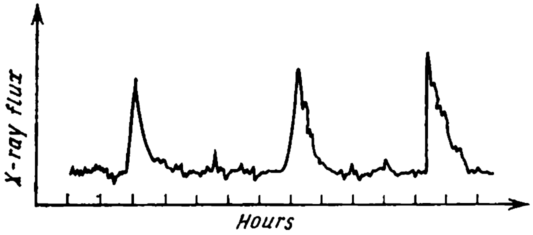


Fig. 78. A burster's X-radiation

million stars. Outside globular clusters in the Galaxy there is only one star in a volume that is 100 times larger.

Before long, bursters were discovered in other globular clusters. Given our knowledge of the distances to these globular clusters, it is possible to estimate the energy generated by a burster. During a burst, the luminosity is some 30000 times the luminosity of the Sun. Between bursts the bursters fade to some constant level, which exceeds that of the Sun several thousandfold. Today we know of 20 sources of this type; some of them are not associated with globular clusters.

The Italian astrophysicist Laura Maraschi first uncovered the secret of the bursters.

She noticed that the total radiation energy of a burster between bursts was 100 more than its energy output during a burst. It turned out that this magic number was characteristic of many bursters and this number was the key to the mystery.

Suppose we have two power stations which differ in efficiency. Given that they burn the same amount of fuel, the ratio between their power outputs will, in fact, be the ratio between their efficiencies. The number 100 is, approximately, the ratio of the efficiency of the accretion onto a neutron star to the efficiency of fusion reactions.

The burster "operates" in the same manner as a recurrent nova, only the white dwarf is replaced by the neutron star. Between bursts, a quasistationary accretion onto the neutron star takes place. The result is hard X-radiation, the "background". Unconsumed hydrogen and helium fall onto the neutron star's surface from its partner. When the temperature and density in the surface layer reach a critical point, explosive fusion reactions consume nearly all the accreted matter which has fallen between bursts transforming into heavier elements within one hundred seconds. The explosion is accompanied by a rise in the X-radiation intensity. The burning takes place at the layer's base, so the resulting radiation "thermolizes" and attains a blackbody spectrum with the temperature of the envelope (less than 10^7 K).

A neutron star has an area about a million of times smaller than that of a white dwarf; and, therefore, the temperature and density necessary for an explosion are achieved much faster than in the white dwarf. This is why "recurrent novae" on neutron stars burst once every few hours and not once every 100 years.

The reason why bursters are not X-ray pulsars lies in the great difference in the strength of their magnetic fields. On an X-ray pulsar, the magnetic field strength is as high as 10^{12}-10^{13} G. Therefore, matter falls only onto 1% of the whole surface concentrating near the magnetic poles. For the same accretion rate, the temperature and density of the matter in an X-ray pulsar is much higher than those in a burster and, probably, higher than critical values for initiating fusion reactions. For this reason, the matter burns out without exploding. Since the fusion efficiency is 100 times lower than the efficiency of accretion, the light from the fusion is hardly visible against the background of the accretion.

A burster's magnetic field is thousands of times weaker, its magnetosphere is very close to the neutron star's surface, and the matter falls isotropically. This is a difference between a burster and a pulsar. In fact, even such a weak magnetic field can influence the homogeneity of the radiation; therefore, the burster's X-ray flux must "tremor" with a period equal to the rotation period of the neutron star. It is likely that we should soon discover this phenomenon. It has been calculated that bursters should rotate with a period of several thousandths or hundredths of a second. Clearly, the accreting matter will accelerate the neutron star, while the weak magnetic field cannot practically impede it rotating at a very high rate.

It is also puzzling why astronomers failed to prove the binary nature of the bursters for such a long time. No eclipses were noted, but this statistical paradox may, however, be explained. Imagine that a burster is a binary in which a neutron star is accompanied by an extremely light (dozens of times less massive) normal star. Even when it fills its Roche lobe, it is much smaller than the binary's size (Fig. 79). It is easy to see that the probability that such a small star will obscure the X-ray source is not high. On average, one in ten systems should be eclipsing. In 1982, one such system was found! Its period is only 50 min (slightly longer than a school lesson).

Let us see how it was proved that a burster is a neutron star. I have already said that during bursts the X-radiation spectrum is close to that of a blackbody, i.e. it obeys the Stefan-Boltzmann law. Given the temperature and the luminosity, we can find the area and, consequently, the radius of

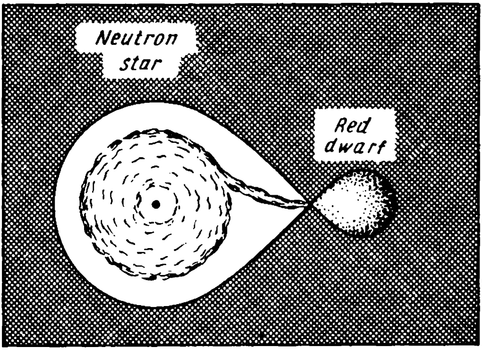


Fig. 79. Outflow of matter in an X-ray burster binary system

the radiating star. It turned out to be about 10 km, which had been predicted by neutron star theory.

As to the origin of such a system, we may choose between van den Heuvel's nonconservative scenario and Schatzman's mechanism, but which one? Observational data put specific restrictions on our ideas. Here we should mention the following puzzling fact: half of all X-ray bursters are concentrated in globular clusters which only contain 1/1000th of the stars in the Galaxy. This is the bursters' third peculiarity. We need to explain why bursters are so unequally distributed between globular clusters and the rest of the Galaxy.

Neither of the two scenarios so far covered for a neutron star's formation in dwarf systems seems to explain this disproportion. Hence a third scenario was necessary and this was that a red dwarf is occasionally captured by a neutron star. The probability of capture is directly proportional to the square of the density of star distribution. In globular clusters, the density is hundreds of millions of times higher, therefore, the bursters form there. As for those bursters that occur elsewhere, they may have been ejected from globular clusters. It is also possible that these outsiders may have arisen according to either Schatzman's mechanism or van den Heuvel's scenario.

But for General Relativity

All the systems mentioned in this chapter are binaries in which the second mass exchange, implying the filling of the Roche lobe by the normal star, has occurred. Matter often flows from a smaller star to a larger one. This happens, for example, in X-ray bursters, U Geminorum systems, polars, etc. In Chap. 4, which was devoted to the first exchange, we showed that a flow from a smaller star to a larger one causes the system to "move apart". The flow rate is the same as the rate at which the star expands to fill its expanding Roche lobe. This occurs on the nuclear timescale. We know that in the systems described in this chapter a normal star's mass is about a tenth of that of the Sun, and its nuclear time is longer than the age of the Universe. On the other hand, observations of mass-flow rate indicate that typical durations of mass change in these systems are about 10^8-10^9 years, i.e. hundreds of times less!

This does not mean that we have erred, simply that we have to take into account general relativity. The Polish astrophysicist Bohdan Paczynski first noticed that in very close systems with periods less than ten hours, gravitational waves must be important. Just as accelerating charges produce electromagnetic waves, an accelerating mass must generate gravitational waves. These waves use much of the system's energy, and it contracts. It is this contraction that compensates for the binary "moving apart" due to the mass transfer. The flow continues on a scale of the energy radiation by the gravitational waves. The calculations based on a formula derived by Einsten for the binary's emission of gravitational waves are in conformity with the observed typical mass transfer rate. Scientists are now building gravity wave detectors and I hope gravitational waves will soon be discovered.

The fact that such waves exist, however, is obvious today, since hundreds of thousands of the binaries in the Galaxy would be unable to exist but for the gravitational waves.

The second mass exchange in low mass binaries leads to the formation of powerful X-ray sources. We shall now turn to the second exchange occurring in massive systems in which flows of matter falling onto relativistic stars are millions of times stronger.

Chapter 7
Cosmic Miracle

The Algol paradox and β Lyrae's spectral properties indicate that the first exchange resulting in a change in roles is a reality. Such an exchange allows massive systems to survive the first explosion and to continue evolving. This is confirmed by the existence of such massive X-ray systems as Centaurus X-3 and Cygnus X-1. In these systems, optical stars, i.e. blue supergiants with masses in excess of $(15\text{-}20)M_\odot$, are losing matter via a stellar wind at a high rate. A relativistic star capturing even a small fraction of this wind will flare brighter than a thousand suns. The accretion rate onto a relativistic star amounts to $10^{-10}\text{-}10^{-9}\ M_\odot$ per year. The accreting star's luminosity is directly proportional to the accretion rate (see formula (15)). The nuclear evolution makes the supergiant fill the Roche lobe; thus the second exchange will begin, and matter will flow from the more massive star to its less massive companion. If this happens, the stars, as we already know, will get closer, which will not allow the star to go under the Roche lobe. As a result, the star starts losing mass on the thermal timescale. For a massive star, this means dozens of thousands of years. If all this matter were to fall onto the surface of a relativistic star, the accretion rate would be $10^{-4}M_{\odot}$ per year, i.e. millions of times higher than in an X-ray system. We shall not be so naive as to believe that under these conditions the relativistic star's luminosity will be millions of times greater. Our assumptions concerning the accreting star's brightness cease to be valid when we are talking about enormous luminosities. As the luminosity and accretion rate grow, the pressure of the accretion-induced radiation must grow too. If the radiation pressure exceeded the gravity matter could no longer fall. It follows that an accreting star's luminosity cannot be infinite. A similar luminosity limit also exists for ordinary stars. It was discovered by Eddington when he studied the equilibrium of high-luminosity stars.

The force of the light pressure acting on a hot plasma is proportional to the amount of light falling per unit area, or illuminance. Illuminance is inversely proportional to the square of distance to a star. This means that light pressure falls with distance in the same manner as gravity. If the light pressure exceeds the gravity at some distance, then it exceeds it at any distance. Therefore, the critical luminosity (the Eddington limit) does not depend on distance but only depends on star mass:

$$L_E \simeq 33000 L_\odot \left(\frac{M}{M_\odot}\right). \tag{19}$$

In other words, a star with the mass of the Sun cannot be more than 33000 times brighter than the Sun, or else it would be torn apart by the radiation pressure.

An accreting star cannot be much brighter (say, 100 times brighter) than the Eddington limit either. Since the star's luminosity is proportional to the accretion rate, the flow of matter cannot exceed the accretion rate corresponding to the Eddington limit. The maximum accretion rate for a relativistic star of a star mass is of the order of $10^{-8} M_\odot$ per year. On the other hand, an optical supergiant star, having filled the Roche lobe. does not know anything about the Eddington limit for its partner and may deliver 10000 times more matter than its partner can possibly accept!

We still do not have a complete theory for a supercritical accretion rate and maybe observations will help us because systems of this kind must exist somewhere in the Galaxy at the moment. The second exchange lasts for about a supergiant's thermal time, i.e. about 10000 years. I hope you still remember how to count stars. All in all, there are about 1000000 massive binaries, each living 10^8 years. It follows that there should be about 100 stars in the Galaxy involved in the second exchange. Even if we admit that the second exchange stage for the massive binaries is dozens of times shorter than the thermal time, there must still be at least one such system in the Galaxy!

Moving Four Ways At Once

The discovery of the remarkable properties of the source SS 433 was the most striking development in astrophysics in the late 1970s. Its spectral properties were astounding even for people with vivid imagination. Yet, not for all.

As you probably know, the Universe is expanding. This fact was predicted by the Soviet physicist and meteorologist Alexander Friedmann* and established by the American astronomer Edwin Hubble in 1929. He discovered that distant galaxies are moving away from us and that the greater the distance between the galaxies and the Solar System, the higher the recession velocity. This is known as Hubble's law and it allows us to determine how far distant galaxies are by measuring their recession velocity.

* It shows that the weathermen are not always wrong. True, he gave no detail and only held that the Universe may be nonstationary, i.e. that it either expands or shrinks.

In 1963, the American astronomer Martin Schmidt deciphered the spectrum of quasars. It turned out that their spectral lines are shifted toward the red end of the spectrum by tens of nanometres, which, according to the Doppler effect, indicates that quasars are moving away from us at tens of thousands of kilometres per second. According to Hubble's law, quasars are the most distant and luminous objects in the Universe. During the following 15 years, hundreds of quasars have been discovered and carefully studied, and all of them only show redshifts.

Frequently great laws make us dogmatic. It was taken for granted for a long time that in the Universe there may be no large (tens of thousands of kilometres per second) shifts toward the blue side of the spectrum. Let me illustrate the point with a story about a Moscow meeting of scientists on finding and contacting extraterrestrial civilizations. One session was devoted to the idea of "cosmic miracle" proposed by Shklovsky. According to Shklovsky, the fact that we see nothing miraculous in space indicates that so far there are no extraterrestrial intelligence (at least, civilizations with whom it would be worthwhile to "chat a little"). This sounds convincing. To support its existence, a supercivilization would have to make some "superefforts" and would leave some trace in the

Universe. Then we would have observational evidence of "cosmic miracles" or, in other words, objects or phenomena that are clearly defying the laws of inanimate nature. But we don't see any. True, the optimists maintain that we could not recognize a miracle. Would it be a square galaxy, or a UFO?

We already have a square or rather rectangular nebula (a disc viewed edgewise). It is more difficult to establish whether a "flying saucer" has been detected for the lack of professional observational data.

In the heat of the argument someone invented the "miracle of miracles", namely, an object whose spectrum would contain both red- and blueshifts indicating motions at velocities of tens of thousands of kilometres per second. It seemed impossible that any object could be flying simultaneously to and away from us at such a deadly pace. Intelligent species would know this. And we realize that they realize that we... and so on. It follows that if there is a sighting investigators cannot attribute to known phenomena, then intelligent species have left it there on purpose to let us know... What we should do is to wait a little until such an object is discovered.

We did not have to wait long.

Less than half a year later such an object was discovered. It seemed to stay in place, move away and toward us, all at once. It moved in all directions like someone spellbound in *The Arabian Nights*.

To Meet Again

In the early 1970s, American astronomers set out to look for celestial objects with

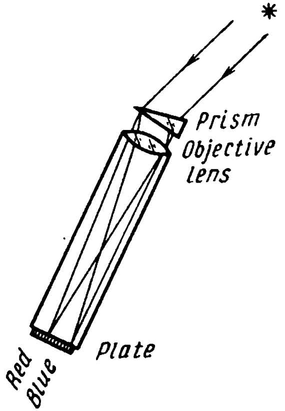


Fig. 80. A spectrograph with an objective prism

bright emission lines with a spectrograph and an objective prism. This is an ordinary telescope with a large prism placed in front of the objective lens (Fig. 80). If there were no prism, the photographic plate at the focus of the objective lens would show just a sector of the starry sky. The prism, however, splits a star's light into colours. The plate carries many pictures of each star in different colours, i.e. the stars' spectra. Although the spectrum of each star is not of the best quality, the advantage of the method is that many stars can be seen at the same time. A star's spectrum is its "fingerprints" which permit us to study its properties.

You already know that bright emission lines indicate some extraordinary phenomena. Today we have a catalogue of such strange stars.

In this catalogue, No. 433 is the variable star V 1343 Aquilae. It was enough to look at the plate to see bright emission lines of hydrogen and helium. It took astronomers several years to find that in the direction of V 1343 Aquilae there are an X-ray source and the remnants of a supernova known as the radio nebula W 50. In 1978, Italian astronomers scrutinized the spectrum of the SS 433 (here SS stands for the initial letters of the names of the catalogue's authors) and were puzzled because the bright hydrogen and helium lines in the spectrum were supplemented with unidentified lines. The Italian astronomers wishing to draw the attention of other investigators to this star published their data in a special bulletin of the International Astronomical Union.

A response came from a group of American astronomers headed by Bruce Margon.

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They carefully investigated the object and deciphered its spectrum (Fig. 81). The unidentified lines turned out to be the same lines of hydrogen and helium but shifted toward the blue and red ends by several tens of nanometres. It looked as if every

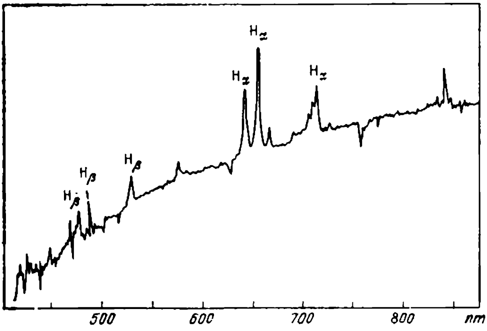


Fig. 81. The spectrum of SS 433

hydrogen transition were yielding three lines instead of one: the brightest line being located where it should be, while the other two lines shifted in opposite directions by great "distances" corresponding to velocities of several dozens of thousands of kilometres per second. You can imagine how amazed astronomers were when they later saw the shifted lines "crawl" to each other!

When this information was made public, the quickest comment came from Mordehai Milgrom, an astrophysicist known for his unorthodox ideas. He suggested that the lines "moved" periodically and were bound to be back where they had been first detected.

Soon American astronomers proved that his suggestion of periodicity of the lines

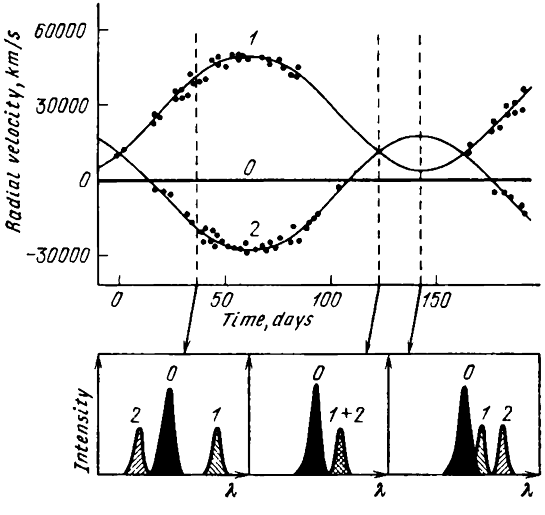


Fig. 82. Radial velocity curves plotted for the two systems of SS 433 lines

moving through the spectrum was absolutely correct. The period was close to 164 days. The radial velocity curves constructed by the red and blue components were close to sinusoids changing in antiphase (Fig. 82).

Not only were the spectra shifting by a half-period per phase, the curves had the same amplitude (about 40000 km/s) and were spaced wider apart along the y axis making up a chain of alternating unequal links. The links' meeting points corresponded to the point where the radial velocities of the both shifted components coincide (see Fig. 82). The most remarkable thing, however, was that at the meeting point there were two and not three lines. This is the case when it is enough to know the number of those meeting to know exactly what they are going to do.

All these remarkable properties helped astronomers to realize why the lines "moved" and where the shifted lines had come from.

Why Two?

Now we shall try to understand why we see the lines three times in the spectrum of the SS 433. Modern physics knows of three mechanisms by which spectral lines can be split in an astrophysical situation. They are the Doppler effect due to motion, a gravity-induced shift, and the Zeeman effect.

The Zeeman effect occurs in a matter placed in a magnetic field. If we put an atom in a magnetic field, the electron's motion will be governed by both the nuclear attraction and the magnetic forces. The splitting of the atom's energy levels is followed by the splitting of spectral lines occurring as a result of transition to these levels. When lines are split in a strong magnetic field, the relative shift of the lines, $\Delta\lambda/\lambda$, depends on the line's wavelength (the level's energy). Different lines of the same atoms have different shifts. This is in contradiction with the observational data in which blue- and redshifts of different lines are alike.

This property is more typical of a gravitational redshift, in which a photon given off by an atom in a gravitational field has to do work to overcome the gravity and lose the "kinetic energy" defined by Planck's formula. Since photon's velocity cannot be reduced, its frequency and wavelength are changed. Although extremely small and hardly detectable for ordinary stars, the shift can reach several tens of nanometres for relativistic stars.

An outside observer will see a gravitational shift in which the photon's energy is always reduced, i.e. an increase in wavelength, or a redshift. So how do we account for the blueshifts in the spectrum of SS 433?

The Doppler effect is the only mechanism left for the shift. This means that V 1343 Aquilae must have three separate radiating regions. The first is practically stationary and gives us the lines that are not shifted.

The other two regions move in opposite directions at gigantic velocities, and their radial velocity components must be equal in magnitude and opposite in direction.

I have already mentioned an interesting feature of the radial velocity curves: when the "moving" lines meet, they are still shifted in relation to the stationary component. That this couple "seeks privacy" seems to run counter to the Doppler mechanism of line shifting. If the radial velocities are in antiphase, they can meet only when their radial velocities are zero. Besides their position should coincide with that of the stationary line, whose radial velocity is always zero. In contrast, the shifted lines show evidence of a great positive radial velocity of about 20000 km/s when they meet. This paradox is resolved by special relativity. Special relativity must be invoked because the observed velocities are significant fractions of the velocity of light.

In special relativity, the static observer on Earth measures the time in a moving reference frame a factor $1/\sqrt{1 - v^2/c^2}$ slower (v is the total velocity). Hence, the electromagnetic wave's frequency, or the wavelength, will be shifted toward the red end of the spectrum. This effect still occurs even if the radial velocity is zero, i.e. the source is moving across the line of sight. Therefore it is known as a transverse Doppler effect. The correct formula for the Doppler effect is

$$\frac{\lambda_{\text{rec}}}{\lambda_{\text{source}}}=\frac{1+v_{\text{rad}}/c}{\sqrt{1-(v/c)^2}}. \qquad (20)$$

In this formula, v_{rad} is, as before, the radial velocity, and v is the total velocity of the source.

Where the moving lines meet, the radial velocity is zero, and the received radiation's wavelength is determined by the total velocity v. Now we can find the total velocity of the source by measuring the line's wavelength at the meeting point. (In practice, we don't even have to wait for the lines to meet. It is enough to find the arithmetic mean of the wavelengths of the red and blue components, which will be the wavelength at the meeting point.)

The total velocity turned out to be 80000 km/s, i.e. about one third of the velocity of light.

A Kinematic Model

The radial velocity curve indicates that the radiating regions producing the shifted spectral lines move in opposite directions while the velocity's radial component changes strictly periodically.

We might surmise that SS 433 is a triple star system in which one star is much more massive than its partners. The less massive stars revolve with a period of 164 days (Fig. 83) and the shifted line components are formed by the less massive companions

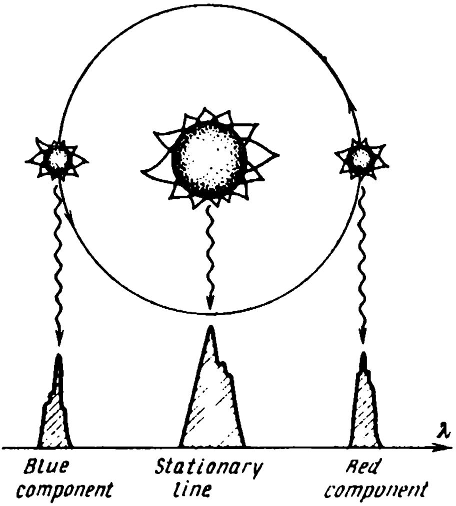


Fig. 83. A triple star system as described by the kinematically incorrect model of SS 433

which move in antiphase along the same orbit while the unshifted lines are generated by the central star.

This arrangement, however, cannot be justified quantitatively. Given the orbital velocity (80000 km/s) and the orbital period, we can use Kepler's third law (see formula (2)) to find the central star's mass. It is equal to $10^{10}M_{\odot}$, i.e. only an order of magnitude less than the mass of the Galaxy. Clearly, this quantity is far too large, but even this is not the only argument against the model.

Let us estimate how much time it takes light to travel across the triple system's orbit along the diameter. The stars complete an orbit at 80000 km/s in 164 days. A diameter is a factor π smaller than the circumference. In other words, light can travel across the system in $(164/3.14 \times 80000/300000) = 14$ days. The radial velocity of one of the stars would thus be zero 14 days earlier than of its companion, which is in contradiction with observational data. Thus, this arrangement is incorrect kinematically.

It is obvious that the only way we can get a less massive object is to give up the erroneous assumption of a 164-day orbital period. Otherwise we shall never get below the $10^{10}M_{\odot}$ mark. One model is a gaseous ring (or a disc) revolving about some unusual body at a velocity of 80000 km/s (Fig. 84). The central body radiates two high-energy beams that cross the ring in two small areas and make these areas hot and luminous. It is easy to see that one of these spots will generate redshifted lines and the other blueshifted lines. Now imagine that this system rigidly rotates about a certain axis with a period of 164 days. This will result in the periodic movement of the lines in the spectrum.

Yet, in this model, too, the central body's mass is unreasonably large. Luminosity in the shifted lines exceeds that of the Sun

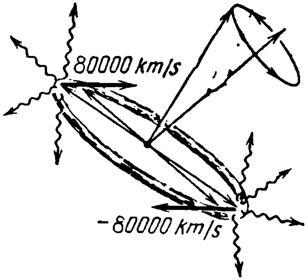


Fig. 84. Another erroneous model of SS 433: a gaseous ring illuminated by a beam of radiation

hundredfold, while the temperature, judging by the spectrum, is close to 10000 kelvins, that is only one and a half times more than the temperature of the Sun's photosphere. The radiating regions thus cannot be much smaller than 10 radii of the Sun. The ring's radius must be at least 10 times larger, i.e. approximately 100 radii of the Sun. This is close to the size of Earth's orbit. The Earth revolves about the Sun at a velocity of 30 km/s, while the gas in the ring of the same radius at a velocity of 80000 km/s. In this model, the central body's mass must be $(80000/30)^2 =$ 7000000 times larger than the Sun's.

To reduce the mass still more, we have to admit that the orbital velocity is not

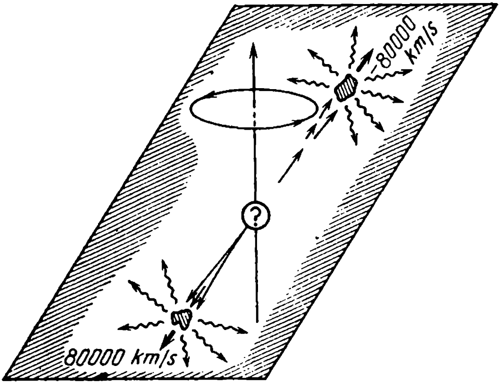


Fig. 85. Matter is ejected into space in two opposite directions

80000 km/s. Thus we arrive at a correct model. Imagine a body ejecting gas jets in opposite directions at 80000 km/s. Once ejected, the gas expands, cools down, and recombines. This is where the shifted lines come from. The ejected jets revolve about some axis (Fig. 85) with a period of 164 days. This changes the radial component of the jets' velocity. The jets are slow enough for the gas to give off its energy before the jets travel very far.

In the mechanics of rigid bodies, there is a phenomenon called precession: the axis of a rotating body subject to an applied torque changes periodically its direction and begins to sweep out a cone. This periodic change in direction is called a forced precession. Free precession occurs when the body's rotation axis does not pass through its centre of mass.

In our case, the 164-day rotation of the lines of the ejected jets was in advance called precession, and the 164-day period the precession period. Today nobody doubts this kinematic model, but the origin of the rotation of the directed jets still causes argument.

We are sure that SS 433 really ejects the gas jets at subrelativistic velocities because we see them. True, they are not visible in optical light but in the radio and X-ray ranges (Fig. 86) the picture is clear. The visible light is generated comparatively near the central body which is why we cannot see the jets even through the best telescope under optimal weather conditions. The radio waves are generated further away, and the capabilities of a radiotelescope are much better. It gives us a distinct image of separate blobs of matter leaving the centre, the direction of the ejected jets changing with a period of 164 days. From our knowledge of the ejected matter's velocity and its angular displacement, we can find how far away SS 433 is.

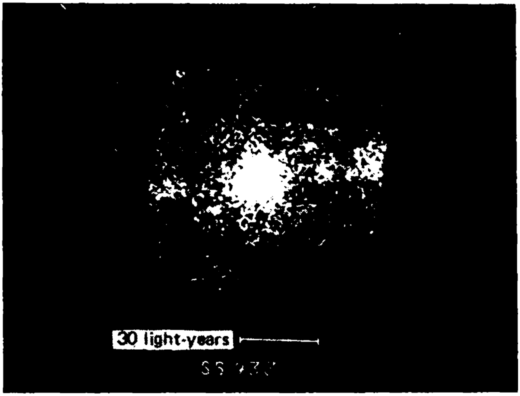


Fig. 86. An X-ray image of SS 433 made from aboard the Einstein orbital observatory

It is 10000 light-years away, i.e. SS 433 is in our Galaxy. (Our Galaxy is 100000 light-years across.) Nobody has ever seen anything like that in our Galaxy. To get a better idea of what is happening, we needed a clue or something familiar in its behaviour.

Something Familiar

There are no poor telescopes, there may be unskilled observers looking through them. This was proved by the Soviet astrophysicist Anatoly Cherepashchuk, who made a very important discovery shedding light on the nature of SS 433 using a small (by modern standards) telescope.

Within the first months of the "gold rush" around SS 433, American astronomers found that the central unshifted lines trembled slightly with a semiamplitude of 70 km/s and a period of about 13 days. The light was later reported to fluctuate with the same period. These data, however, were not reliable and were not much of a clue. What astronomers needed was long-term observations.

This was done with a small reflecting telescope with a 600-mm mirror. Unofficially, a telescope with a mirror of more than two metres in diameter is large, one with a mirror between one and two metres in diameter is medium, and all the rest are small.

The advantage of small telescopes is that there are many of them and they are not too busy. To make sure the light fluctuates with a period of 13 days, you need several months of observations. Not 13 days!

The star's periodic light fluctuations were combined with chaotic changes in light intensity. These may be due to atmospheric scintillations or the intrinsic (sometimes known as physical) variability of a star. Averaging random quantities takes time. If the periodic and chaotic fluctuations have the same amplitude, the light curve may only be plotted after you have observed many periods.

Having spent several months observing SS 433, Cherepashchuk plotted a reliable

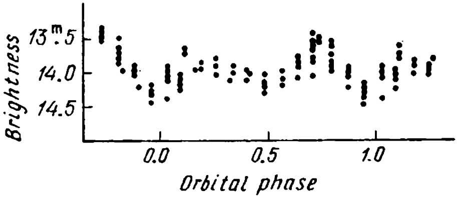


Fig. 87. The light curve of SS 433 obtained by Cherepashchuk

light curve. Its shape resembled Algol's curve and this established that SS 433 is an eclipsing binary system (Fig. 87).

It was the first time that we saw some familiar traits in this mysterious object. The next step was to see what kind of binary it is. We can see no absorption lines in the spectrum of SS 433. At least, no one has ever seen any. The star's continuous spectrum has a maximum in the red range, which indicates a low temperature. As is known, cold stars are usually low mass stars and so SS 433 was initially believed to be a low mass binary.

The mistake was corrected when astronomers took into account the light absorption by interstellar dust. The constellation Aquila is located near the Galaxy's plane where there is a great deal of dust. Given the distance to SS 433, we can determine how much the dust dims the light, in fact, it reduces the light by approximately eight magnitudes, or 1500 times. Relatively more blue light is absorbed by the dust which, by the way, is why the Sun at sunset looks red.

We may thus conclude that V 1343 Aquilae is not red and cold but blue and hot. An analysis of the light curves has shown that the both objects (I choose to call the binary's components this way so far) have a high temperature (more than 20000 kelvins) and nearly equal luminosity in visible light (the depths of the eclipses do not differ much).

Even if one of the components is an ordinary star, it is massive. The star's size is comparable with the size of the binary, which makes one wonder whether the normal star fills its Roche lobe and, like β Lyrae, is flowing into its neighbour.

This, however, seems to contradict the apparent spectrum. The width of the lines' unshifted components corresponds to several thousands kilometres per second. It follows that they occur in the optically thin matter outflowing from the binary. This looks very much like a stellar wind from a blue supergiant. The similarity, however, is misleading. The rate of outflow in SS 433 is hundreds of times that of ordinary supergiants. It amounts to approximately $10^{-4}M_{\odot}$ per year. Such is the theoretically estimated flow of mass from a massive star which has filled its Roche lobe to its less massive partner.

Now let us see whether the mass in V 1343 Aquilae is outflowing from one star to the other or is being ejected into space.

Supercritical Accretion

Before we start choosing between hypotheses, we must know for sure the difference between what we see and what we imagine. It is certain that SS 433, otherwise known as V 1343 Aquilae, is a binary with a period of about 13 days. This period is nearly the same as that of β Lyrae. The system ejects material at a velocity of several thousands of kilometres per second. The outflow velocity is usual for hot O-B stars but the outflow rate is unexpectedly high. If this were the only strange thing about SS 433, we might consider it a binary, though with some reservations.

But apart from the other things, the binary ejects two jets of gas at an extremely high velocity of 80000 km/s for some unknown reason. The direction of the jets precesses with a period of 164 days. The jets radiate in the radio and X-ray ranges. The binary is surrounded by a nebula which looks very much like what remains after a supernova explosion. I'd like to add that the star itself only weakly radiates in the X-ray range. This seems to be all we know for sure about it.

It is possible that one of the binary's components is a blue star of spectral class B with a mass of no less than $10M_{\odot}$. The nature of the second star is little known. The high velocity of the jets and the remnants of a supernova indicate that the companion may be a relativistic star (a neutron star or a black hole).

Why does a relativistic star behave so strangely? Unlike other massive binaries, the relativistic star in SS 433 is not a bright source of X-radiation. Judging by the observational data, the binary's second companion looks very much like an ordinary hot star, and it would be listed as such if it were not for the relativistic jets.

Have a look at Table 2 which lists the physical properties of X-ray pulsars. Not one has a luminosity in excess of the Eddington limit (formula (19))* and there must be an

* The mass of an X-ray pulsar is several times that of the Sun; therefore, its Eddington limit is 50-100 thousand $L_{\odot}$ ($L_{\odot}$ is the luminosity of the Sun).

explanation for this. All X-ray pulsars "work" in the subcritical accretion mode or slightly exceeding the Eddington limit. A relativistic star with a supercritical accretion looks quite different.

Supercritical accretion must occur in a close binary during the second mass exchange through the inner Lagrangian point. In this case the outflow rate exceeds the critical value equal to the Eddington limit by tens of thousands of times. If all the matter were to fall on the relativistic star, the radiation pressure would be as many times more than the gravity. This means that all the matter cannot fall onto the star.

Is it possible that the matter falls and does not fall at the same time? Yes, it is. This can be easily arranged in the case of disc accretion. In 1973, Shakura and Syunyaev presented a qualitative scenario of how this might happen. They considered supercritical accretion onto a black hole (Fig. 88). Far from the black hole, the accretion disc's structure is hardly different from that of an ordinary subcritical disc, and the energy produced in the disc is much less than the Eddington limit, the light pressure being insignificant. At a certain distance, however, the radiation pressure becomes comparable to or exceeds the gravity. Some of the matter is, therefore, "blown off" away from the disc. The remaining matter continues to move toward the black hole. In order for the accretion to be steady-state, i.e. not to vary with time, the mass of the matter falling onto the black hole must be such that the total luminosity of the disc exceeds but little the Eddington limit. This limit was calculated

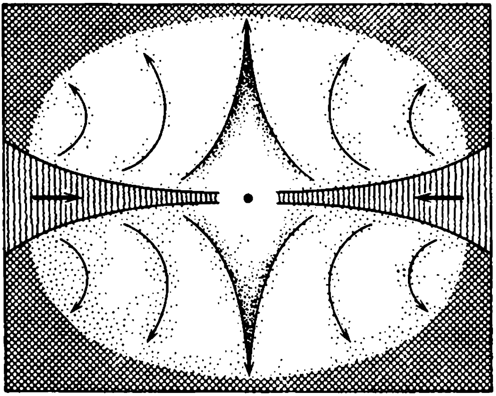


Fig. 88. Supercritical disc accretion

for a static star radiating isotropically. The situation is different for a disc. Therefore, a minor excess over the Eddington limit will not destroy the disc.

Only a small fraction of the matter initially captured reaches the black hole in this "semiaccretion" mode. Almost all the matter is "blown off" in the form of a quaspherical stream resembling a stellar wind. There is so much material that any hard X-radiation occurring in the vicinity of the black hole is almost wholly absorbed by it. Consequently, a relativistic star undergoing supercritical accretion cannot be a bright source of hard X-radiation. An outside observer would see only a "coat" with properties like those of an ordinary star.

An accretion disc has a preferred direction, or an axis. The gas jets are ejected from the central regions of the accretion disc at a relativistic velocity along this axis. This scenario was developed six years before the discovery of the unique properties of the SS 433. Today it might be regarded as a forecast if investigators had not found relativistic jets in galaxies and quasars long before.

A classical example of jet discharge is in the galaxy Virgo A (Fig. 89), which was first observed very long ago. Now we know of dozens of similar examples. True, the jets in the nuclei of galaxies move at relativistic velocities, not subrelativistic velocities. Jets are not ordinary matter and look like blobs of relativistic particles which have "become entangled" in the magnetic fields and been ejected together with them from the nucleus of the galaxy.

The model of jets moving along the axis of a supercritical disc was intended to explain this phenomenon.

If we place a neutron star in the centre of a supercritical disc instead of a black hole, much will remain unchanged. The interior will still be covered by an opaque "coat", and an outside observer would see an ordinary star. The strong magnetic field of a neutron star destroys the supercritical disc

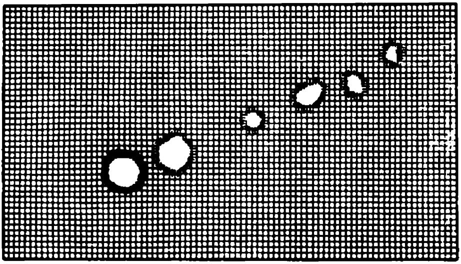


Fig. 89. A jet from the nucleus of the galaxy Virgo A

over distances of several tens or hundreds of times the neutron star's radius. All matter reaching the magnetosphere falls onto the neutron star's surface. This is accompanied by an outburst of energy which is tens or hundreds of times more than the Eddington limit. A fraction of matter affected by the radiation pressure may be ejected along the magnetic axis of the neutron star at velocities of 100000 km/s, i.e. the escape velocity for the neutron star. If the neutron star's rotation axis coincides with its magnetic axis, an outside observer will see jets of matter ejected from behind the "coat" in

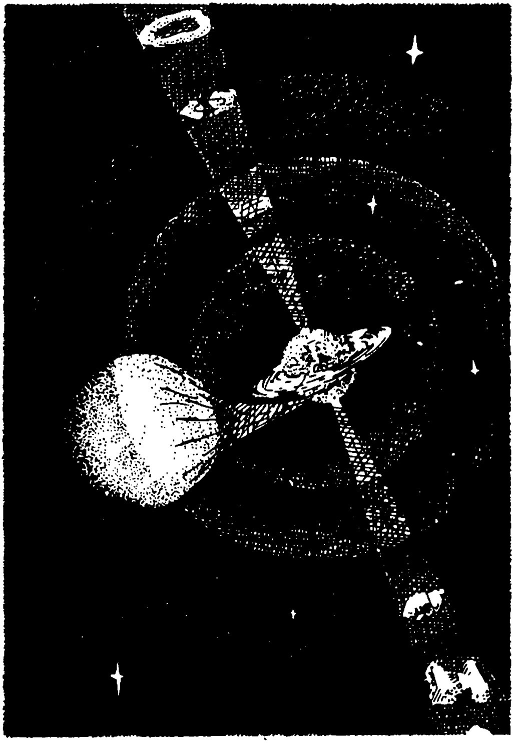


Fig. 90. A binary in a supercritical accretion mode

opposite directions at relativistic velocities (Fig. 90).

SS 433 may be a binary undergoing the second mass exchange accompanied by the formation of a supercritical disc around the relativistic star. This would solve the apparent paradox that, on the one hand, the unshifted lines indicate the presence of a stellar wind and, on the other hand, the value of the mass-flow rate indicates mass exchange between the components. This is what we expect from supercritical accretion. The matter, in the form of a "gravity wind", flows from the normal star to the relativistic star and then is almost completely ejected in the form of a stellar wind from the relativistic satellite.

How long can such a process last? Nobody knows exactly. It may be tens of thousands of years, or thousands of years. If we bear it in mind that it takes light 10000 years to travel from SS 433 to the Earth, we may conclude that now the mass exchange in SS 433 is already over. Today we see what was happening 10000 years ago.

At present, we don't know for sure what is (or was) underway in the V 1343 Aquilae system. It is not yet clear why the jet direction "moves" with a period of 164 days. There are many hypotheses but, probably, the phenomenon is similar to the 35-day cycle of Hercules X-1. If the normal star's rotation axis does not coincide with that of the binary, the normal star starts precessing because of the tidal force acting from the relativistic star. Both the direction of the matter jets and the plane of the accretion disc will rock together with the star.

Such a "slaving" disc in the Hercules X-1 periodically obscures the X-ray pulsar from us and changes the direction of jets in SS 433. This attractive hypothesis is rather popular. Yet I believe it has many drawbacks, and probably here we deal with an absolutely different phenomenon.

These questions still await final answers, but every year makes us more certain that SS 433 is the first massive system in which we have come across the second mass exchange accompanied by the formation of a supercritical disc. Let us see what happens to the binary next.

The "Nightmare" of the Second Exchange

The second exchange in a massive binary is always accompanied by a loss of mass. The relativistic star is physically unable to accept all matter that leaves the normal star, and radiation pressure ejects it from the system. Besides the mass, the system also loses its angular momentum which causes the binary's components to move closer together. This reduces the Roche lobe, but the normal star does not respond quickly to this reduction and loses still more mass, which brings the stars still closer together.

The process continues ever more quickly until the relativistic star finds itself inside the supergiant; the supergiant "swallows" the tiny neutron star.

Thirty years ago this idea would have seemed fantastic. Now attitudes are different. Many hundreds of hours of computer time have been spent trying to understand what happens to a relativistic star "swallowed" by a supergiant. The situation seems simple in that the normal star's structure and its density distribution are known. The relativistic star's motion will be similar to that of a satellite reentering the Earth's atmosphere. The satellite is decelerated by the atmospheric drag and approaches the Earth along a steep spiral, its speed increasing all the time. The reason for this is the same as the reason for a star's negative heat capacity.

The satellite's kinetic energy grows due to the work done by gravity, but a relativistic star differs from a satellite in one very important aspect (which complicates the situation enormously): the satellite entering the Earth's atmosphere does not change its physical structure. The satellite burns up producing energy which is insignificant as compared to the energy binding the atmosphere to the Earth. Things are different with stars. A relativistic star inside any ordinary star is dangerous ecologically. The energy produced by the compact star's deceleration is so great that the normal star starts losing its matter. This alters the star's structure and the deceleration force. A rigorous solution of such a dynamic problem is only possible by a computer which can operate at billions of operations per second. There are not so many such computers and the calculations so far done are rough approximations and only be considered qualitative research.

The relativistic star entrains the supergiant's material with its gravity. One layer after another is accelerated and pulled away from the star for good. Like a sharp knife cutting lemon peel, the compact star slices away the supergiant's upper layers. Eventually the "swallowed" star arrives at the centre.

Do you remember that by the time the second exchange begins, there is a helium nucleus at the centre of a massive star? The reason is that the exchange begins after the star has expanded to the size of the Roche lobe or, in other words, has left the main sequence. Let us see what will happen when the relativistic star reaches the nucleus.

Here the following alternative is possible. Either the binary containing a helium and a relativistic stars occurs, or the relativistic star is "swallowed" by the helium nucleus once and for all and "settles down" at the supergiant's centre.

An interesting result of stellar "cannibalism" was considered by the American astrophysicist Kip Thorne and his colleagues. They calculated what the structure of a supergiant which "swallowed" a neutron star would be. The source of energy in such a "cannibal" would mainly be matter accretion onto the neutron star. By the way, Landau first suggested in 1937 that accretion by a neutron star inside an ordinary star might be the reason for a whole star's energy generation.

How long does a "cannibal" star live? These "freaks" will live for a long time if the accretion is slow. The matter must support the neutron star's radiation by settling on its surface slowly.

Suppose "cannibalism" is a rare exception. A binary remains a binary. Then comes the next stage in a close binary's evolution when a helium star is orbiting with a relativistic star. The possibility that such stars may exist was stressed by the Soviet astrophysicists Tutukov and Yungelson. Helium stars (Wolf-Rayet stars) intensely lose their matter in the form of a stellar wind. It seems that after the second exchange the relativistic star must again become a bright X-ray source. Yet no hard X-radiation has so far been discovered from a Wolf-Rayet star. So perhaps stellar "cannibalism" may be the rule rather than the exception.

Chapter 8

Wanderers

We have traced a binary's evolution via β Lyrae and Algol through X-ray binaries like Centaurus X-3 and Cygnus X-1 and have come to the critical point, the second mass exchange. This is when the binary's life is at stake. The second exchange may only be compared to the explosion of one of the binary's components. The second exchange is accompanied by supercritical accretion onto the relativistic star and, probably, by it being "swallowed" by the normal star—supergiant.

Whether a binary can survive can only be determined by observations. If it can, the result will be a binary of a helium and a relativistic star. What we need to do is to look for them in the sky. The helium stars must be Wolf-Rayet stars and there are many of them. It would be easier if they differ in some way from other binaries. Fortunately, systems with relativistic stars do have distinguishing features, namely, birthmarks which they obtained during earlier stages of their evolution. In the late 1970s astronomers used these features to restrict their search and they had an astonishing success.

Runaways

We live in a spiral galaxy. Most of its stars make up a plane figure, which is shown edgewise in Fig. 91. The flat disc is surround-

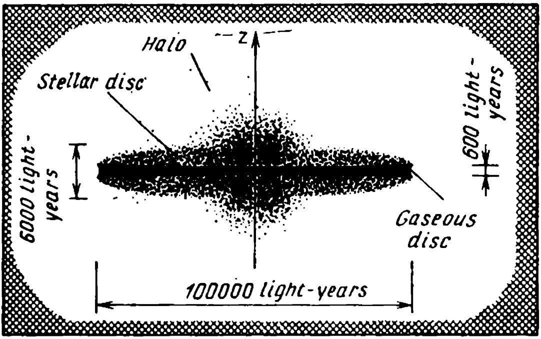


Fig. 91. The structure of the Galaxy

ed by a less massive spherical subsystem called a halo. In the last few billion years, stars have only been born in the Galaxy's disc. The disc is only of the order of three thousand light-years in thickness and one hundred thousand light-years in diameter.

In order to describe intragalactic phenomena, astronomers use a coordinate system in which the z axis is directed along the axis of the disc. Then it is usually said that the thickness of the star disc along the z axis is three thousand light-years. New stars, however, are born in a much thinner layer that is several hundred light-years thick, i.e. 5-10 times thinner. The reason is that the gas which is a kind of material you need to form a star is concentrated in a thin disc several hundred light-years thick.

The disc is rotating. This means that each star revolves in a gravity field created by the other stars of the Galaxy. Alongside the general revolution, each star moves at a low random (chaotic) velocity. But for this, the star disc would be infinitely thin. Random star motions smear the disc to its apparent size. Young stars move randomly 10 times more slowly than the revolution velocity which is close to 200 km/s nearly in the whole Galaxy. The greater the star's random velocity, the further along the z axis it can travel.

The average random velocity of massive stars in the Galaxy does not exceed 5-10 km/s. A star moving at such a velocity cannot move more than several hundred light-years. Indeed, most massive stars are concentrated in the vicinity of the plane of the Galaxy. Yet there are some exceptions.

There are stars in the Galaxy which move tens of times faster. They are called runaway stars. At such velocities they can climb to altitudes of thousands of light-years above the plane of the Galaxy. They do not leave the Galaxy, but they do not remain in the "herd".

Blue runaway stars of spectral classes O and B were carefully studied by the Dutch astronomer Adrian Blaauw in the 1950s. Although there are only a few of them, they constitute several percent of the normal stars of the same spectral class.

Could this be due to the cumulative effect in Pokrovsky's experiment, or when coins jump onto the floor in the underground, or which turns multiple stars into binaries (see Chap. 1)?

Can anything like this happen in the Galaxy? Although each star's momentum is small, when stars collide or, to be more exact, when they approach each other, they can transfer momentum from one to another and some may attain velocities of several hundreds of kilometres per second and so leave the Galaxy's plane.

This simple explanation for runaway stars is wrong quantitatively. Star collisions are so rare that they cannot explain the observed number of runaway stars. This was understood by Blaauw, who found another explanation.

He suggested that the runaway stars used to be components of close binaries. At that time, the idea that a change of roles, which explained the Algol paradox, could happened had not been generally accepted. Blaauw suggested that the binary's more massive component evolves faster and that there is no mass exchange. Then the more massive star explodes first. Most of the binary's mass is ejected, and the system disintegrates (see Chap. 4, Section "The Story Will Be Continued"). The bond binding the system's components (gravity) is broken due to the radically decreased gravity caused by the tenfold loss of mass by one of the stars. The stars or, to be more exact, the normal star and the collapsed remnant fly away like a stone from a sling. Each star's velocity is about its orbital velocity, which in close binaries is of the order of hundreds of kilometres per second. This is Blaauw's explanation for runaway stars.

But we now know about the Algol paradox and role changing, and that the first explosion in a binary does not lead to its disintegration. Thus there is role changing but no Blaauw mechanism. If so, there are no runaway stars either.

In fact, the Blaauw mechanism as such does not seem to be correct but role changing may in itself be used to explain runaway stars. After the mass has been ejected, the binary acquires additional momentum but does not disintegrate (Fig. 92). The ejection must occur quickly because the

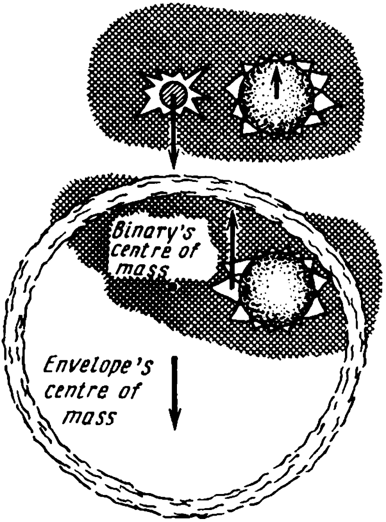


Fig. 92. The effect of "recoil" caused by the ejection of matter by one of the stars in a binary. Before the explosion, the envelope's matter had been moving with the star along its orbit and thus had a certain momentum. If the matter is ejected rapidly, the envelope takes this momentum, and the remaining binary starts moving in the opposite direction according to the law of momentum conservation. As a result, the centre of mass of the envelope-and-binary system as a whole remains static. Note that the envelope is ejected symmetrically about the exploded star

ejected mass takes the orbital momentum with it. According to the law of momentum conservation, the binary must acquire a recoil momentum in the opposite direction. If it does, it will develop additional velocity of several hundred kilometres per second. On average, binaries with relativistic components must have greater velocities and z coordinates.

"Single" Wolf-Rayet Stars

Now it is clear where to look for binaries with relativistic and helium stars. They are among the Wolf-Rayet stars moving rapidly and having large z coordinates.

These, however, are not their only "birthmarks". During the second mass exchange, the binary ejects a great amount of matter into the surrounding space. This matter must be observable for at least an astronomically short period of time. Some "wanderers" must be surrounded by matter that appears as nebulae.

The "single" Wolf-Rayet stars fit this pattern. They are said to be single because their spectra show the lines of only one star. Either the star has no component at all, or the component is so weak that its lines are invisible against the background of the bright emission lines of a Wolf-Rayet star. These stars were for a long time considered singles because no trace of an eclipse or radial velocity variation had ever been recorded. In 1978, astronomers set out in search of binaries among the "single"

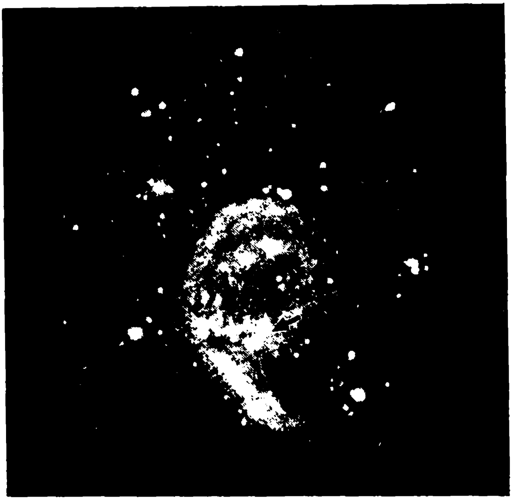


Fig. 93. A photograph of the ring nebula NGC 6888 surrounding the "single" Wolf-Rayet star HD 192163 (shown with the arrow). The photograph was made by Tatyana Lozinskaya (at the Crimean station of the Sternberg State Astronomical Institute)

Wolf-Rayet stars. Some of them are surrounded by ring-shaped nebulae (Fig. 93). The nebulae could be the matter ejected by binaries during the second exchange. These stars were selected as the most prospective binary candidates.

Very soon a binary was discovered. The star numbered 50896 in the HD (Henry Draper) catalogue and surrounded by a

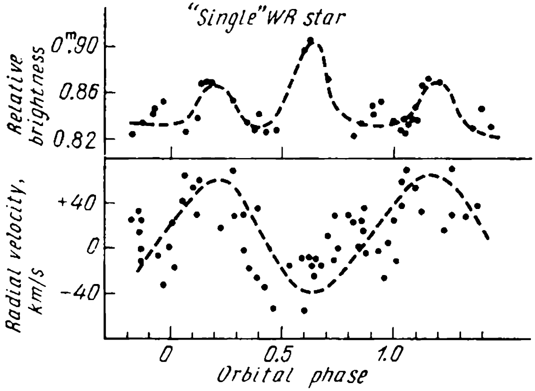


Fig. 94. Light and radial velocity curves of the "single" Wolf-Rayet star HD 50896

planetary nebula RCW 11 was changing its brightness and radial velocity with a period of 3.8 days (Fig. 94). It is enough just to look at the radial velocity curve to see how difficult it was to uncover the binary nature of this "single" star. The widths of the lines in the spectrum correspond to thousands of kilometres per second and the semiamplitude of the radial velocity variations is only 35 km/s. You must be very skilled and very optimistic to notice and trust the trembling of the lines which amounts to only several percent of its width. It is like trying to find the width of a razor edge with a school ruler.

Note that the time of the secondary minimum in the light curve (see Fig. 94) coincides with the passage through a gamma-velocity in the radial velocity curve. This is excellent evidence for the eclipsing nature of the minimum. Astronomers in various countries have found about ten "single" Wolf-Rayet stars with periodic variations in their radial velocities and brightness (Table 5).

The most amazing thing concerns the mass function obtained from the measurements of radial velocities. For all stars, the mass function is much smaller than the mass of the Sun, which indicates that the second component has a small mass.

Now let us do some arithmetic. In a close binary containing a massive star and a neutron star, the relativistic star's orbital velocity can be as high as 300 km/s. Since the orbital momenta of the binary's components are equal, the orbital velocity of the normal star, which is tens of times more massive, must be the same tens of times lower. It follows that the massive star's radial velocity amplitude must, therefore, be several tens of kilometres per second, which is exactly what we see in Table 5.

Table 5. "Single" Wolf-Rayet stars with possible relativistic companions

Star	Apparent magnitude	Period, days	Amplitude		z axis, light-years	Mass function, $M_{\odot}$	Presence of ring nebula
			light, magnitude	velocity, km/s			
HD 50896	6.9	3.8	0.08	35	−900	10^{-2}	yes
HD 192163	7.7	4.5	0.03	20	200	10^{-2}	yes
HD 191765	8.3	7.4	0.04	30	100	7×10^{-3}	yes
HD 197406	10.5	4.3	0.06	90	3300	0.3	no
HD 96548	7.8	4.8	0.04	10	1000	3×10^{-4}	yes
HD 164270	9.0	1.8	0.05	20	700	10^{-3}	no

If here we deal with relativistic stars, it is not clear why none of them radiates in the X-range. Wolf-Rayet stars supply their relativistic neighbours with vast amount of matter, and their stellar winds are tens of times stronger than those of O-B supergiants, near which bright X-ray sources can be found.

This discrepancy makes us doubt that Wolf-Rayet stars have relativistic companions. Is it possible that astronomers have found something they were not looking for? This happens fairly often, indeed, radio pulsars were discovered this way. Investigators were looking for scintillations and they discovered neutron stars.

However, in this case there are too many points of contact between theory and observation. So it was asked whether there must be any X-radiation at all? The astronomers' reasoning was as follows. Given that the stellar wind from a Wolf-Rayet star is very intense and dense, could it be too dense? Then it won't let X-radiation pass through, just as the Earth's atmosphere blocks off X-radiation. This explanation became widely accepted because it allowed us to see things clearly. A relativistic star capturing the stellar wind matter radiates in the X-range with a luminosity hundreds of times that of the Sun. All the X-radiation, however, is absorbed by the stellar wind and is reemitted in, say, the optical range. The relativistic star's eclipse causes the system to fade several percent (several hundredth of magnitude) in the visible range, which is in conformity with the variations in the apparent light intensity of the "single" Wolf-Rayet stars.

It was after the binary nature of the "single" stars had been discovered that the hypothesis of the X-radiation self-absorption began to crack. The observational data gave us the components' period and velocity, which allows us to find the distance between them. The result was 10-15 times the radius of the Sun, while theoretically Wolf-Rayet stars should be 2-3 radii of the Sun in size. So the relativistic star is not that deep in the envelope outflowing from the helium star. However, at such a distance, the stellar wind is already transparent to hard X-radiation, and the relativistic star should be visible in this wavelength range.

Some investigators sought an answer in another direction. Suppose all the "single" binaries so far discovered contain neutron stars. We know that in order for matter to fall onto a neutron star's surface, at least two conditions must be met: first, the material must be available to fall and, second, the neutron star must not rotate too quickly as otherwise the magnetic field would cast the material in different directions due to the propeller effect. In systems with Wolf-Rayet stars, the first condition is satisfied but the second one is not. Recall that during the second exchange, i.e. at the stage immediately preceding the formation of a binary with a helium star and a relativistic star, the system undergoes supercritical disc accretion. As a result, the neutron star receives both mass and angular momentum. The second exchange gives the neutron star a high-rate axial rotation. The propeller effect prevents the star from being a bright X-ray source. So you see that the binary's evolution itself is such that no bright X-ray source appears after the second exchange. If it does, it happens very seldom.

The research on the single Wolf-Rayet stars still continues, and astronomers may get a clearer picture in years to come.

The Second Explosion

A helium star's evolution inevitably results in the exhaustion of its nuclear energy and collapse. This is what happens during the first collapse. The central iron core turns into a neutron star, and 90% of the matter is spewed out into space. The difference is that now the more massive component of the binary explodes. The total energy of the remaining stars becomes positive, which causes the binary to disintegrate. The new neutron star becomes a young radio pulsar.

It will produce radio pulses for several millions of years, but this is not all.

The most amazing thing is that the second explosion may bring about two radio pulsars, not one. This result of a binary's evolution was first described by the Soviet astrophysicists Gennady Bisnovaty-Kogan and Boris Komberg in 1974. They started from the observational data. Some of the X-ray pulsars in binaries have periods of less than four seconds and are still accelerating. On the other hand, radio pulsars also have periods less than four seconds. This means that a neutron star may become a radio pulsar if the optical component is "taken away" from a Hercules X-1 binary with an X-ray pulsar.

This is done by nature. The optical component is "eliminated" by itself after the second explosion.

Hence, massive binaries are good producers of radio pulsars. Note that their efficiency exceeds 100%.

Another general conclusion is very tempting. Suppose that all (or almost all) radio pulsars come from binaries. Strange as it might seem, there are no serious objections to this because it is statistically true.

If every massive binary gives birth to one or two radio pulsars, their birth-rates must be approximately equal. Let us see how we can estimate the birth-rate of pulsars. We already know how to count stars and so we divide the number of radio pulsars in the Galaxy by their average lifetime. Unfortunately, it is difficult to estimate the total number of pulsars in the Galaxy because we only see the nearest ones and not all at that. Pulsars radiate in narrow beams and we do not see even nearby pulsars if their beams do not strike the Earth. We could take this into account by finding the probability that the Earth is hit but it will not be an accurate calculation because we lack information about the shape of the pulsar beam.

These difficulties make us treat estimates of pulsar birth-rates with suspicion. Even so most experts are of the opinion that one pulsar is born every 15-20 years in the Galaxy, which is very close to the birth-rate of massive binaries determined by the Salpeter function (see formula (14)). The Salpeter function gives us the following birth-rate for binaries with a mass more than $10M_{\odot}$: one system every 30-40 years. Of course, these are only estimates.

In general, there are many coincidences in astronomy. The well-known Soviet astrophysicist Ernest Dibai used to joke that if we took two arbitrarily chosen numbers and multiplied them together while preserving their dimensions, we would get a third quantity which is what astronomers observe. This joke has a grain of bitter truth. You will hardly count all ideas ruined by such coincidences. This "law of large numbers" may easily be explained. Many quantities

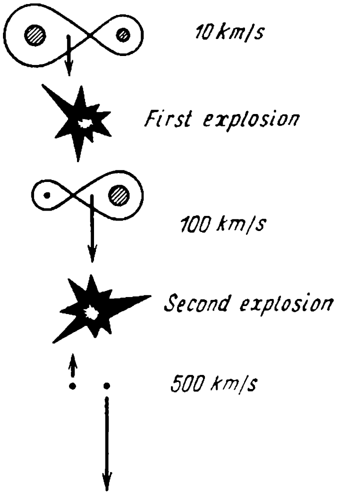


Fig. 95. As a result of two explosions, a radio pulsar may reach a velocity of several hundreds of kilometres per second

in astronomy are known to an accuracy of the order of magnitude and are extremely large. So how do we know whether $10^{21\pm1}$ is the same as $10^{20\pm1}$?!

Yet if massive systems are the ancestors of radio pulsars, we would get a much clearer picture. For example, we know from observations that there are many radio pulsars whose intrinsic velocities are several hundreds of kilometres per second. This would mean that radio pulsars are also "runaways", but we know where they come from. A radio pulsar may attain a high velocity in two ways, viz. during the first explosion (together with a binary) or during the second explosion (disintegration) (Fig. 95). A lucky pulsar could be accelerated to a velocity of 500 km/s, which is exactly the velocity of the fastest pulsars.

Binary Radio Pulsars

None of the radio pulsars found in the first five years following their discovery were components of binaries. It seemed that some inexorable law caused radio pulsars to avoid binaries.

This strange "law" was violated in July 1974 when the American radio astronomers R.A. Hulse and Joseph Taylor discovered the pulsar PSR 1913+16.* Its average period was 0.059 s, and the period's instantaneous value varied, in turn, with a period of 7.75 hours.

In 1974, this was not a riddle. The study of X-ray pulsars showed that these variations result from the Doppler effect

---

* PSR stands for a "pulsar", and the numbers are its right ascension $\alpha = 19^h13^m$ and declination $\delta = +16°$.

and the pulsar's orbital motion. Figure 96 shows the radial velocity curve right after the discovery of the pulsar. It differs from a sinusoid, which means that the pulsar's orbit is very elliptical. The system's mass

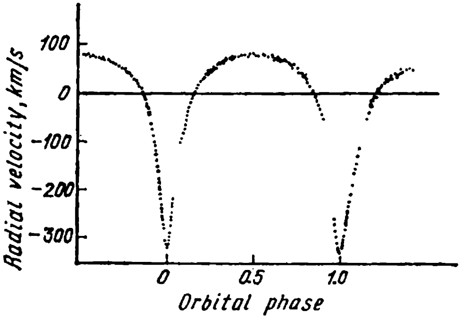


Fig. 96. The radial velocity curve of the radio pulsar PSR 1913 + 16

function is $0.13M_{\odot}$. As soon as it became clear that it was a binary, investigators began looking carefully for a companion in each of the electromagnetic wavelength range, but in vain.

When discussing the Algol paradox, I said that in order to collect all information about a binary both components must be observed. The mass function, which is obtained from the apparent radial velocity of one of the stars, is a function of three unknowns, namely, the masses of the components M_1 and M_2, and the angle of the system's inclination i. You cannot find the mass of either star from the radial velocity curve, and yet this curve is the only source of information about a pulsar and its invisible companion available to the researcher.

Yet the pulsar's mass has been measured. The mass of its invisible companion has also been measured, and the accuracy of these measurements was unprecedented. Indeed, these are the only stars in the whole Universe whose masses are known to within a few percent.

The reason for this is that the pulsar's intrinsic radiation is extraordinarily steady-state. If instead of considering the period we speak about its frequency, we may say that the pulsar behaves like a star that gives absolutely thin spectral lines. Basically, the width of a star's spectral lines is determined by the thermal motions of the atoms in its atmosphere. Thermal motion usually has a velocity of several kilometres per second and so the line is "smeared out" by $\Delta\lambda/\lambda \simeq v_T/c = 1/1000$ around the central wavelength. "Smearing" a pulsar's rotation period caused by the slowing down of its rotation occurs in the course of 200 million years. The width of the pulsar's "spectral line" is the reciprocal of the "smearing" time; so the relative width is about 10^{-17}!

Since this line is so thin, we may measure the pulsar's radial velocity with a very high accuracy. All we need is a long period of observations or, in other words, a large number of received pulses. The accuracy achieved in the first year of observations was such that effects described by special and general relativity could be measured. Measuring new effects is like adding new equations for unknowns. The mass function determined by the classical Doppler effect gives us a relationship between three quantities. What we need is another two equations.

Here the transverse Doppler effect comes to rescue. The pulsar's apparent period depends on both the radial velocity and the pulsar's total velocity. If a pulsar moved along a circle and its total velocity were constant, the transverse Doppler effect would be useless. For we do not know the pulsar's "true" period! But a pulsar's orbit is largely eccentric. This means the total orbital velocity changes, and so we must observe a periodic change in the pulsar's period: at the periastron (when the stars are closest together) the pulsation period is longer than at the apastron.

Time dilation in a gravitational field is another relativistic effect; we covered it when we were discussing the gravity-induced redshift. Then we spoke about it in terms of energy (a quantum reddens because it does work against gravity). In terms of general relativity, quantum reddening occurs because time in a strong gravitational field flows more slowly than it does for a distant observer.

So the measurement of the relativistic Doppler effect and the gravity-induced red-shift gives us another equation. But in reality the classical Doppler effect changes the pulsar's apparent period with the same period (the binary's period) as the relativistic effect does. They are inseparable. If we only could have a look at the binary "from the side"! Then the classical Doppler effect will change while the relativistic effects will remain the same. We would be able to divide these effects and obtain an additional equation.

Strange as it might seem, this is possible. There is another quite observable relativistic effect which makes a "space voyage" unnecessary. According to general relativity, Newton's law of universal gravitation is not applicable in strong fields and is not accurate in weak fields. A binary's gravity at the distance of semimajor axis is not strong because the orbital velocity is a thousand times less than the velocity of light.

In fact, gravity is not exactly inversely proportional to the square of distance. Under such conditions, the binary's orbit cannot be closed (Fig. 97). It looks as if the orbit's ellipse were turning slowly in the binary's orbital plane. This is the same as to fly around the binary and see it from all sides.

This means that we can both differentiate the classical and the relativistic Doppler effect and have a third equation to find all three parameters, i.e. both masses and the inclination angle.

The pulsar's elliptical orbit makes one revolution in 86 years. I hope you

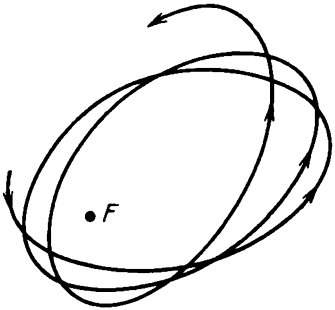


Fig. 97. The effects of general relativity result in the star's orbit being open

understand that we do not have to wait that long. Measurement accuracy is such that only a few years of observation can be used to find the masses of the binary's components. They happen to be similar and equal to $(1.42 \pm 0.10)\ M_{\odot}$. The obtained masses are in impressing conformity with the theory of stellar evolution and structure.

In recent years, investigators have discovered two more pulsars which are components of binaries (Table 6). Characteristically, the companions of these stars do not reveal themselves either.

Table 6. Binary radio pulsars

Pulsar	Orbital period, days	Pulsar period, s	Eccentricity	Mass function, $M/M_{\odot}$	Mass of second star, $M/M_{\odot}$
PSR 1913+16	0.32	0.059	0.617	0.1322	1.4
PSR 0655+64	1.03	0.196	0.000	0.0712	1 ± 0.03
PSR 0820+02	1.232	0.865	0.012	0.0030	0.2-0.4
PSR 1953+29	appr. 120	0.006	<0.05	0.0027	0.2-0.4

A binary radiates gravitational waves. General relativity predicts a certain intensity for this radiation. The binary loses both energy and angular momentum. The stars "slide" toward each other, with an accompanying reduction in the system's period.

The radio pulsar's stability helped measure a binary's period and its changes very accurately. The period does indeed decrease, and this is happening in compliance with Einstein's theory.

Options

Only a few of the 400 known radio pulsars are components of close binaries. All of the binary radio pulsars hide their partners. It is probable that these invisible components are stars which have come to the end of their evolution such as white dwarfs, neutron stars, or black holes. This means that occasionally binaries do not disintegrate after the second explosion.

I hope you remember that a system disintegrates if the explosion happens very quickly and more than a half of the system's mass is lost. The second condition will be satisfied if the second explosion is preceded by an evolutionary loss of a great deal of mass by the normal star. This may happen during the second mass exchange.

We know that the second exchange usually ends with a binary consisting of a helium star and a neutron star. The helium star's mass is no less than (8-10)$M_{\odot}$. Clearly, the explosion of such a star will destroy the system. Given that a would-be supernova's mass is of the order of (2-3)$M_{\odot}$, the star association will survive.

Do you still remember the scenario suggested by van den Heuvel for the pulsar Hercules X-1? If the star masses had differed much initially, the system would have lost much of its matter already during the first exchange (see Fig. 67). Thus a massive binary would have become a system with medium mass.

Imagine an explosion in the HZ Herculis—Hercules X-1 system. The system's total mass is (3.5-4) $M_{\odot}$, of which the neutron star accounts for $1.5M_{\odot}$. If the collapse turns the second star into a neutron star with a mass of $1.5M_{\odot}$, this means the system, if explodes, will lose (0.5-1) $M_{\odot}$, i.e. less than a half of the binary's mass. Thus the system will continue to be binary.

This scenario has one peculiarity, namely, the resulting system of two degenerate stars always has an elliptical orbit. It is made elliptical as a result of the rapid loss of mass. True, if the system lost half of its mass, its total energy would be zero and the orbit's eccentricity (formal) would be unity. If less is lost, the circular orbit becomes elliptical.

The system remembers this eccentricity. The orbits of the pulsars PSR 1913 + 16 and PSR 0820 + 02 are truly elliptical (see Table 6), while the orbit of the radio pulsar PSR 0655 + 64 is circular. It looks as if the binary in the second collapse either lost no mass or it lost it slowly. A third possibility is that there was no collapse at all. Shklovsky called the first possibility a "quiet collapse" and it must end up with the formation of a black hole. The second possibility was supported by the Italian astrophysicist Franco Pacini and it may occur when the collapsing star rotates very quickly. Then centrifugal forces stop the collapse, and the star continues to shrink gradually only as it is losing its angular momentum. When I say "gradually", I mean slowly enough for the collapse and the resulting loss of mass to go on longer than one revolution of the system. Then the effect of the mass loss is averaged and the orbit remains circular.

Finally, the third variant is also possible. If the normal star's mass before its nuclear sources are exhausted is less than the Chandrasekhar limit, there is no collapse. The star shrinks slowly into a white dwarf.

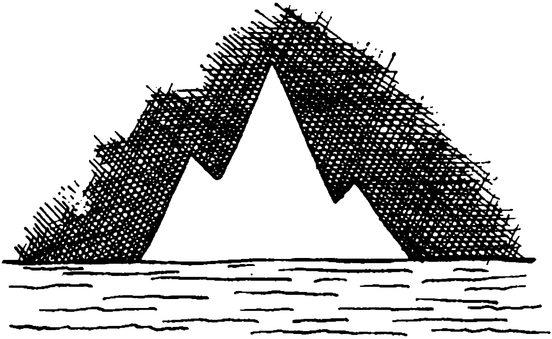
You see that there are various alternatives. The later the stage we look at in a binary's evolution, the more difficult it is to see how a binary could have so evolved.

Anyway, it is small wonder that there are so few binaries consisting of a radio pulsar and a compact star. This is accounted for by the following. First, binaries composed of stars that differ greatly in mass are rare. Second, a binary's evolution is long and full of hardship, and the binary runs the risk of disintegrating during the first mass exchange.

Generally speaking, a binary's later evolutionary stages are still poorly understood. Many ideas do not make up for few calculations. Let us see how all this may end.

The inner (nuclear) evolution of the binary's components has ended. Our current understanding is that the inner evolution is the slow exhaustion of fuel in the depths of the star as it burns out. The next stage of the evolution may only be a gradual approach of stars to each other caused by gravitational wave radiation. A moment comes when the stars collide. The coalescence occurs almost instantaneously, during the degenerate star's hydrodynamic timescale. For a neutron star and a black hole it equals about 10^{-5}-10^{-4} s. Their coalescence is followed by a strong gravitational pulse which takes almost all the energy of the binary. What remains is, most probably, a black hole which, like a radio pulsar, becomes a wanderer.

The coalescence of binaries containing white dwarfs may be more varied. Their material still has a nuclear structure and their coalescence may be accompanied by the emission of neutrinos and the ejection of matter into space. In principle, this phenomenon may be called a supernova explosion.



Glaring Peaks

Our story is drawing to a close. We have traced the evolution of a binary star from the first stages when the components still live "separately" to the final stages when they can't live apart.

Their binary nature is enriching. This is even more so at the final stages of the evolution. Their evolutionary paths branch, and the range of possibilities looks very much like a tree with a beautiful crown. Many branches are poorly studied. Some of the branches are doomed to "wither and

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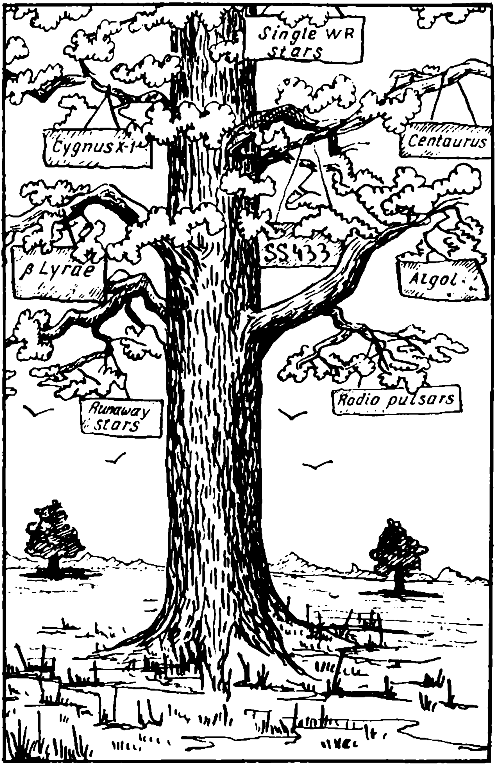


Evolution scenario

fall". For this reason, when discussing a binary's evolution, I have sought to keep to the major paths. Now let us review matters. What else might be seen on this evolution tree? Have we overlooked anything important?

Summing Up

A binary's evolution is like a film shown at an increasing speed (Fig. 98). The stars go through the first evolution stages on the nuclear timescale. This takes massive stars tens and hundreds of millions of years, and less massive stars billions of years. A more massive star will fill its Roche lobe first and will begin the first mass exchange. We considered this when we were discussing the β Lyrae system.

There are various outcomes of the first exchange. In systems with a large ratio between the masses of components, the binary loses a great deal of matter (a scenario resulting in systems like Hercules X-1). As a rule, the system's total mass is not reduced radically. The exchange ends up with systems with a pronounced Algol paradox: the less massive star seems older than its partner. Its evolution has gone so far that its partner can't catch up with it even if it has increased its mass. Depending on the binary's mass, the evolution of the initially more massive star ends in a white dwarf, a neutron star, or a black hole; white dwarf ancestors have masses less than $10M_{\odot}$.

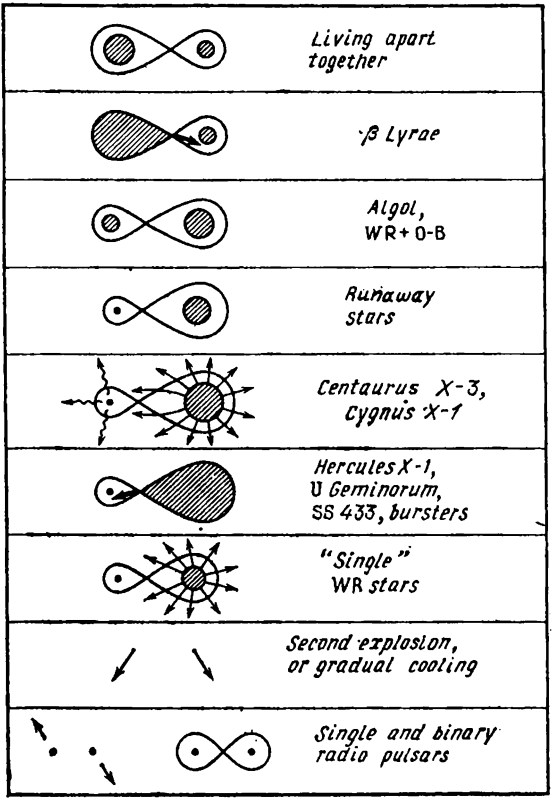


Fig. 98. The evolution of close binaries. Some observational data are given on the right

The formation of the first relativistic star, even though accompanied by an explosion and the ejection of matter into space, does not cause the system to fall apart because it is the less massive star that explodes. This lucky circumstance connected with role changing brings about some qualitatively new phenomena in a binary.

My story now continues. Next comes the X-ray stage with binaries like Centaurus X-3 and Cygnus X-1. Strong sources are brighter than a thousand suns while capturing a small fraction of the stellar wind from the neighbouring star. The first explosion, however, will leave "birthmarks": the binary will acquire additional velocity and will begin wandering throughout the Galaxy.

As a result of its nuclear evolution, the normal component leaves the main sequence and inevitably fills its Roche lobe. The second mass exchange begins. The normal star returns the matter previously taken from its neighbour.

In low mass binaries with neutron stars, the second exchange results in the formation of a bright X-ray source (an X-ray system like Hercules X-1 or an X-ray burster). In systems with white dwarfs, the second exchange leads to the formation of cataclysmic variable stars, recurrent novae, novae, etc. In dwarf binaries, the second filling of the Roche lobe does not usually arise due to nuclear evolution (it is too slow) but due to the stars' "rapprochement", which is caused by the binary's loss of angular momentum. The reason lies in gravitational waves and the effect of a magnetic propeller.

In massive binaries, the second exchange is so rapid that it brings about supercritical accretion onto the relativistic star. The latter is wrapped in a dense "coat" of outflowing matter and is invisible to an outside observer. It looks like an ordinary star. At the same time, supercritical accretion may cause relativistic jets. This is not unlikely that we came across this very phenomenon in SS 433.

As a result of the second exchange, the relativistic star is "swallowed" by its companion. This is where a branch forks out. The relativistic star may be totally "swallowed", and the binary becomes a single star, or, having ejected a part of its mass, the binary may turn into a system composed of a helium core and a relativistic star. The most promising candidates for such a binary are "single" Wolf-Rayet stars.

Several hundred thousand years later, the helium star runs out of its nuclear fuel and explodes to give birth to two relativistic stars. The usual result is the formation of, on average, more than one radio pulsar. When the binary disintegrates, the neutron star attains additional velocity. For the first million years, the wanderers continue to send radio signals into space until they become dead stars for ever.

On rare occasions, a binary evolves into a system of two degenerate stars. Here nature gives us a pure experiment of general relativity. Thanks to such systems, astronomers have managed not only to "weigh" a neutron star with an unprecedented accuracy but also prove that gravitational waves really exist.

Much of what I have been telling you in this book has been discovered and studied in the recent 10-15 years. New and quite unexpected phenomena take place in systems with relativistic stars. The discoveries made in this field have caused a "revolution in astronomy", and yet these are but the first steps. Today we know enough to realize that there are still many things yet to be discovered about the world of binaries.

Evolution Squared

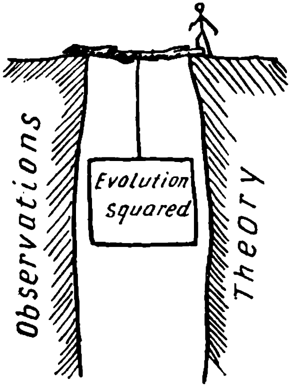
Before telling you about the relativistic stages in the evolution of binaries, I made some calculations of their possible number. My arguments are extremely simple and therefore quite reliable. The lifetime of a binary after the formation of a relativistic star in it is close to the nuclear time of the normal star on whose surface the material has flown. The normal star's nuclear time, however, is not very different from that of the initially more massive star. It follows that there must be the same order of magnitude of X-ray binaries in the Galaxy as there are ordinary massive binaries, or, in other words, tens and hundreds of thousands.

Compared to this, the number of discovered X-ray binaries (several hundreds or thousands) is ridiculous.

We may get a far more sensitive telescope but the difference between what we see and what we expect to see will not disappear. Today we already see all the galactic sources of hard X-radiation with a luminosity several hundreds and more the luminosity of the Sun.

We seem to have missed something really important. A naive approach to the binaries' relativistic stages is ineffective. There must be some reason why a relativistic star in a binary does not necessarily become a source of X-radiation. The latter is rather the exception than the rule. It is not an ordinary star that is to blame. All stars have wind, and all stars may supply fuel for an accreting relativistic star. This means that the relativistic star is not that simple. There must be some other condition or, maybe, a number of conditions required to switch on the accretion machine.

Recent research has helped us understand that compact stars evolve too. It has a great impact on the apparent properties of binaries. The overwhelming majority of relativistic stars in massive binaries are neutron stars. Although the same, each neutron star may behave differently. Before X-ray pulsars had been discovered,

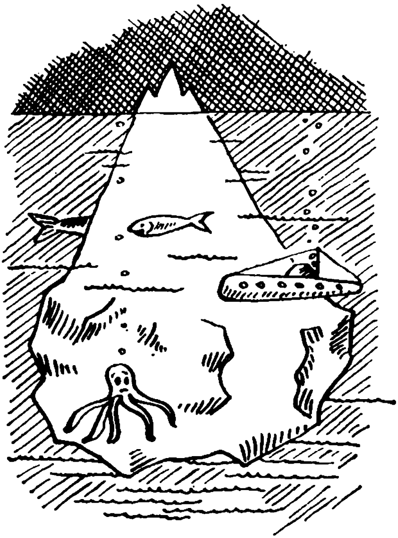


Shvartsman showed that a neutron star in a binary undergoes at least three stages. Initially it rotates very rapidly ejecting electromagnetic waves and relativistic particles into space like a radio pulsar. True, the radio radiation itself is absorbed by the stellar wind from the normal companion. This is one of the main reasons why today we do not observe radio pulsars paired with a normal star.

During its ejection stage, the neutron star loses energy and slows down. At a certain moment, the ejection ends. Yet the material can't yet fall on the neutron star's surface because it scatters the falling plasma by its magnetic field like a gigantic propeller. The star goes on decelerating, and, finally, gravity wins. This is when accretion begins, and a bright X-ray source flares up.

Each of these stages lasts for tens to hundreds of thousands of years. This is a real evolution. We shall add to this the evolution of the normal component. Now we see the life of a binary with a neutron star in a new light. This is more than just one or even two evolutions, it is, rather, evolution squared because the states of the normal star and the neutron star are not directly linked. We must multiply the four evolutionary stages of a binary with a relativistic component (a star in the main sequence, a supergiant, a star at a stage of exchange, and a helium star) by the number of states of a neutron star. True, the state of a neutron star is connected (though not rigidly) with the state of its normal component. Therefore, the number of possible states a binary may have is half this number. This, however, does not change the essence.

In fact, the neutron star may be in at least eight, not three, states. Only one of these states, namely, accretion, is accompanied by strong thermal X-radiation. In other cases which, I must confess, have been less studied, the neutron star is not that noticeable. This is why we first came across the X-ray stages in the Galaxy. They



"Non-X-ray stages in a binary's evolution"

are simply eye-catching. It is a glaring peak, but the peak of an iceberg.

We are now making our first steps to find non-X-ray relativistic binaries, and we already have had some success.

We have already counted the relativistic systems and have seen that they are only a little less numerous than ordinary systems.

Every second or third massive star which seems to be alone has, in fact, a relativistic companion. In the early 1980s, astronomers set out to look for such binaries, and their search was successful. This work is extremely time- and effort-consuming. First they decided to check O-B runaway stars which had been always considered singles.

These stars are accelerated to great velocities during the binary's first explosion. If there had been a collapse, there must be a neutron star. Being attracted by the neutron star's gravity, the massive star must move along its orbit at several tens of kilometres per second. Traces of such motions have recently been discovered in a number of O-B stars.

This, however, is a subject for a book which is yet to be written.

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